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THE INTRUSIVE MECHANICS OF A CLASTIC DIKE

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ABSTRACT. The field relations and petrology of a clastic dike cutting up into a dolerite sill from an underlying conglomerate are described. The probable conditions of temperature and pressure are derived from mineralogical and geological relations, and the dike is shown to have been emplaced while the sill was hot. The intrusive mechanism is deduced to be the expansion of water or water vapor in the pore space of the conglomerate in response to a local drop in pressure resulting from the opening of a fracture in the dolerite. The mechanism is shown to have general application to many clastic dikes commonly ascribed to plastic flowage. Possible applications of this mechanism are suggested to explain other injections of solid material such as early crystalline differentiates with intrusive relations into later rocks of a differentiated sequence, lamprophyre dikes, and certain peridotite intrusions.

FIELD RELATIONS

RECENT quarrying operations in a thick dolerite sill forming the prominent ridge known as West Rock near New Haven, Conn., have exposed an unusually well developed clastic dike of sedimentary material cutting up into the dolerite. This paper describes the field relations and petrology of the dike, from which it is possible to deduce with considerable certainty the mechanics of its injection.

The dike is exposed in the Clark-Barone quarry on the west face of West Rock Ridge, directly east of Konold's Pond, 3.75 miles northwest of New Haven. West Rock Ridge is the outcrop of a dolerite sill 300 to 400 feet thick at this locality. The sill is intrusive into arkosic sediments of the Triassic Newark group of Connecticut. The sill is about 1,000 feet above the base of the Triassic and is overlain by at least 12,000 feet of sediments with some basaltic lava flows. The entire sequence dips eastward 15° to 20° at this point, and the sill crops out in a north-south direction for 16 miles. The locality of the clastic dike is 1.5 miles north of the southernmost extremity of the sill. The region as a whole has undergone virtually no deformation other than high-angle faulting since the beginning of Triassic deposition.

The dolerite is a dark microphanerite of basaltic composition, aphanitic near the contacts, which are chilled. It is a tough, uniform, massive rock characterized by fairly close columnar, or palisade, jointing and irregular cross joints. The sill is underlain in the vicinity of the clastic dike by an arkosic conglomerate derived from the weathering of granites and metamorphic rocks which lie to the east of the Triassic basin in the New Haven area. The arkose has a pinkish hue due to numerous pink feldspar grains and contains abundant quartz pebbles up to 2 inches in cross section, the larger of which appear to be of vein origin. The sediments are fluviatile and most of the pebbles are well rounded.

The contact of the dolerite with the underlying sediments is relatively uniform in general but uneven in detail. It conforms closely to the bedding in the arkose for distances of a few feet to several tens of feet, but breaks sharply across the bedding for a few inches to several feet in places. Sags and swells up to twenty feet in amplitude are also present, though not in the near vicinity of the dike. Figure 1 shows the contact at the point where the clastic dike is found.

The clastic dike is physically continuous with the arkosic conglomerate and is composed primarily of the same material as the conglomerate. It is similar in texture and appearance and clearly derived from the conglomerate. The dike cuts in a somewhat irregular manner but with sharp, clear contacts upward into the dolerite (fig. 2). At the base of the sill the dike strikes N. 35° E. and dips 80° E. Two feet above the base the dip flattens to 55° E. and then steepens upward; 10 to 15 feet above the base the dip is nearly vertical. The irregular character of the dike may be seen in figures 1, 2, and 3, but the true attitude is obscured by the oblique angle at which the dike intersects the surface of the exposure.

At the base of the sill the dike is 3 to 4 inches wide; 2 feet above the base it is 8 inches wide. It tends to narrow upwards fairly regularly and at a height of 30 feet above the base it is only 0.10 inch wide. It passes beneath talus 35 feet above the base so that its entire length and the manner in which it terminates cannot be seen, but it is clearly pinching out where last visible. About 8 feet above the base the dike splits into divergent off-shoots, two of which reconverge to enclose an angular block of dolerite, as shown in figure 3. The dike is

about 1 inch wide at this point. The upper branch continues to the point where it disappears beneath the talus, the lower pinches out in a few feet.

The dike is cut by the columnar jointing in the dolerite and is not controlled in the slightest degree by the columnar jointing. The relationship clearly indicates that the dike formed entirely prior to the inception of the columnar jointing and has no genetic or structural connection with it. When the columnar jointing took place it affected the dike and the dolerite alike. At one point the dike is offset 2 inches, but the plane of slippage along which the offset took place is closed and healed so that no visible fracture is evident. This feature and the relationship to the jointing indicate that the dike formed at a very early stage in the consolidation of the dolerite.

The point at which the dike cuts into the base of the sill is located on a slight upward bulge in the base of the sill, and is about 6 feet from a sharp vertical offset of about 5 feet in the contact (fig. 1). This offset is not the result of faulting subsequent to the consolidation of the dolerite. Both the dolerite above and the arkose below are continuous with no discernible plane of movement. The offset occurred either during the intrusion of the magma or while the rock was still hot enough so that the zone of movement could be healed. The offset is quite sharp at the top, but close examination shows that it is a sharp curve rather than an angular break. As the photograph shows, the lower part of the offset is more gently curved. The clastic dike may be genetically connected to this feature. A similar, somewhat smaller offset is also exposed about 30 feet north of the dike. A few small tongues and dikelets of clastic material besides the one described here are present in the exposure, but they are only inches in length.

PETROLOGY

Megascopically the dike consists of detrital material derived from the underlying conglomerate. It consists of an aggregate ranging from pebbles to grains not discernible with the unaided eye. The maximum size of the pebbles diminishes as the width of the dike diminishes, but the pebbles tend to range in size up to the width of the dike at any given point. Thus at 26 inches above the base of the sill the dike is 3 inches wide and contains a rounded quartz pebble measuring 2.6

inches transverse to the trend of the dike and 2.4 inches in the plane of the dike (fig. 4).

Three thin sections were examined, one from the underlying conglomerate, one from the dike at a distance of about 3 feet above its base where the dike is about 8 inches wide and one from 27 feet above the base where the dike is only 4.5 mm. wide. The thin section of the underlying conglomerate shows rounded to subangular quartz and feldspar grains with a small amount of interstitial coarse-grained secondary calcite, insignificant amounts of opaque minerals and heavy silicates, and traces of a secondary chlorite. The feldspar is very dusty with a low birefringent alteration product, probably kaolin, and a very little sericite. About half is orthoclase and microcline and half sodic plagioclase. The following proportions were found with the integrating stage:

	Volume Percent
Grains 0.1 mm. in cross section or larger	
Quartz	48
Feldspar	16
Calcite	2
Grains less than 0.1 mm. in cross section	34
	100

The fine-grained material and the altered feldspar are a light, dusty, reddish brown in plane polarized light, probably due to thinly disseminated limonite. The rock has undergone a small amount of cementation by secondary quartz. Minute tongues and lobes of quartz project outward from the boundaries of quartz grains and partially enclose or replace adjacent feldspar grains. The secondary quartz is crystallographically continuous with the grains on which it grows, which at first sight suggests that the quartz grains have been corroded and partially replaced, but, as will be shown below, the appearance is due to the accretion of secondary quartz on the original detrital grains.

Three feet above the base of the sill the material in the dike consists of essentially the same minerals, but in the following proportions:

Grains 0.1 mm. in cross section or larger	*Volume Percent*
Quartz	33
Feldspar	6
Chlorite	10
Calcite	2
Opaque grains and heavy silicate	1
Grains less than 0.1 mm. in cross section	48
	100

The most striking differences are the increase in secondary chlorite and the gain in fine-grained material at the expense of quartz and, to a larger extent, feldspar. The feldspar is more strongly altered and sericite is more abundant, but clay is the predominant alteration product. Close examination of the fine-grained material shows that there is considerable secondary interstitial quartz in irregular grains enclosing the original detrital minerals. Some relatively coarse pockets of calcite are present and associated with them are small quartz crystals showing sharp crystal faces, including prism faces. Hydrothermal deposition of quartz is indicated, with low quartz the stable form.

Twenty-seven feet vertically above the base of the sill the clastic dike is only 4.5 mm. wide. It consists of quartz sand grains up to 2.0 mm. in cross section, altered feldspar, small opaque grains, and abundant radiating clusters of chlorite. Interstitial quartz in relatively large, irregular grains forms an indistinct matrix crowded with the original detrital grains and alteration products.

The following table shows the mineral content without regard to grain size. The figures are not strictly comparable with the previous volumetric analyses. The percentage of quartz is probably too large, for dusty inclusions, too minute to count, are abundant.

	Volume Percent
Quartz	43
Chlorite	30
Feldspar and alteration products	25
Opaque	2
	100

Estimated percentage of grains less than 0.1 mm. in cross section: 50%. Calcite is not present and sericite is more common in the altered feldspar.

The quartz sand grains have an unusual aspect. A shell of secondary quartz, crystallographically continuous with the original detrital grain, has grown around each grain up to a thickness of 0.4 mm. At first sight it appears as though this shell were a reaction rim of alteration products partially replacing an outer zone of an originally larger quartz grain, because the shell of secondary quartz is crowded with fine-grained, dusty included material. However, the included material consists of grains of altered feldspar, limonite, and

other original detrital material. On the other hand, these outer shells of quartz have relatively less secondary chlorite than the rest of the rock. The secondary nature of the dusty shells around the quartz grains is further indicated by the fact that the inner boundary of the shell is perfectly sharp and smoothly rounded in the form characteristic of water-worn quartz sand, while the outer boundary of the shell is irregular and makes sutured contacts with other grains of secondary quartz. Fractures and zones of inclusions which are primary features in the quartz terminate at the inner boundary of the secondary shells. Where two original detrital grains are close enough so that their secondary shells come in contact, the contact is very finely sutured and intergrown. If the rims enclosing foreign material were the result of alteration or replacement of the margins of originally larger grains, the outer boundaries of the rims should preserve the original detrital form and the inner boundaries should be irregular and embayed. The reverse is true.

In some cases the original quartz sand grain is composed of more than one crystal of quartz. In these cases the optical orientation of the surrounding quartz shell is not uniform, but corresponds to the optical orientation of that part of the original grain on which it grew. This relationship is suggestive of a replacement origin for the shells, but the other evidence is believed to preclude this possibility and to show that the crystallization of quartz on the nucleus supplied by the original grain was controlled by the orientation of the nucleus, even in the case of heterogeneous grains.

Orthoclase feldspar and sodic plagioclase including pure albite were detected, but very few grains are large enough or fresh enough for determination.

The chlorite in the section from the underlying conglomerate is in minute plates with rectangular habit, positive relief against quartz, and very low birefringence. It is distinctly pleochroic with $X =$ pale greenish yellow to white and $Y = Z =$ light, clear green. It is more abundant and coarser in crystallization in the sections from within the dike, where it takes the form of fan-shaped aggregates and vermicular clusters. Interference colors range from a slightly anomalous bluish-gray to a peculiar greenish-yellow. Elongation is positive with respect to the perfect (001) cleavage. The min-

eral resembles negative penninite except for the rectangular habit of small crystals and the higher birefringence of some of the material. It is clearly a secondary mineral which grew at the expense of the finely divided groundmass of the sedimentary material, with the addition of magnesia. The varying birefringence and habit found in these sections suggests that varying proportions of iron and alumina are present, and if classified according to Winchell (1933, pp. 276-286) the mineral is chlorite varying from antigorite to penninite or possibly chamosite in composition.

The section from 27 feet above the base contains an inclusion that was apparently derived from the enclosing dolerite. It consists of an indistinct aggregate of pyroxene relicts, now composed of antigorite, and lath-shaped relatively fresh plagioclase. The outline of the inclusion is very indefinite. It appears to be merely a somewhat dispersed cluster of mineral grains derived from the dolerite. The indistinct form of the inclusion may be partly due to alteration, but it seems to be at least partly caused by mechanical disintegration during movement of the dike material.

Megascopically the contact of the dike with the dolerite appears to be sharp, tightly welded, and not a zone of mechanical weakness. Microscopically it is well defined but not sharp or open and evidence of alteration can be detected in the dolerite for a distance of about 3 mm. from the contact. Some serpentinous alteration is present in the pyroxene of the dolerite throughout the rock, but within 3 mm. of the clastic dike it becomes noticeably more abundant. Within a millimeter or less of the dike much of the pyroxene is completely altered to antigorite. At the contact some of the plagioclase of the dolerite is slightly altered, chlorite is intergrown with the original dolerite minerals, and secondary quartz is interstitial to the mineral grains of the dolerite in contact with the dike.

A small but appreciable proportion of the dike is made up of drusy cavities filled with secondary calcite and other minerals ranging in diameter from about 4 mm. to submicroscopic. The calcite is leached out on weathered surfaces giving the dike a slightly pitted aspect on close examination. A specimen from the dike was sawed in a plane perpendicular to the walls and the surface polished. It was then leached for

several hours in strong hydrochloric acid to remove carbonates and reveal the cavities on the fresh surface. An area of about 50 sq. cm. was traversed with a binocular microscope fitted with a micrometer grid ocular. About 3.5 percent of the area was found to be cavity space. This estimate may be low because of cavities below the resolving power of the microscope, but it is a minimum index of the volume of the rock made up of secondarily filled free space.

Attached to the walls of the cavities and surrounded by calcite are several secondary minerals. Well-formed, prismatic quartz crystals terminated by the positive and negative rhombohedron, characteristic of low-quartz, are the most abundant and largest. There are also abundant radiating acicular clusters of well-formed epidote crystals. The mean index of refraction is 1.755 +, indicating it is about 30 percent ferrian in composition. An X-ray rotation photograph about the B axis gave an axial length of 5.65, in close agreement with published values. The outer portions of some of the larger quartz crystals were observed enclosing parts of radiating groups of epidote, indicating that the growth period of quartz extended beyond that of epidote.

Small blue-green nodular clusters of chlorite and very minute, well-formed pyrite and garnet crystals are encrusted on the cavity walls. Their period of growth appears to be somewhat later than epidote and quartz.

In addition to the other secondary minerals identified in the cavities, there were a few crystals of sphene growing attached to the walls and with the same paragenetic relations as the epidote. An X-ray powder photograph is identical with sphene in the Brush mineral collection of Yale University, specimen no. 5681, from Willimantic, Connecticut. The crystals are outwardly well-formed and pale yellowish to buff-white with a pinkish cast. Examination under the polarizing microscope and an X-ray rotation photograph show it to be complexly twinned however. The following forms appear to be present as designated in Goldschmidt (1897, pp. 344-345) and Dana (1892, pp. 712-713): (100), (201), (111), and possibly (001). Only the (111) faces were perfect enough to give definite, though multiple, reflections in the goniometer. The other faces were strongly etched and somewhat concave. The angle nn measured was 44° 19′ as compared with 43° 49′ given in

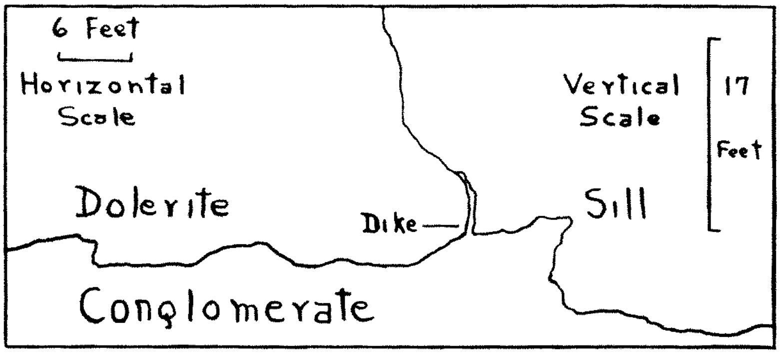

Figure 1. Photograph and sketch showing the lower contact of the West Rock dolerite sill against an arkosic conglomerate. Note the offsets in the contact and the tapering, irregular character of the clastic dike. The vertical scale is foreshortened by the slope of the exposure.

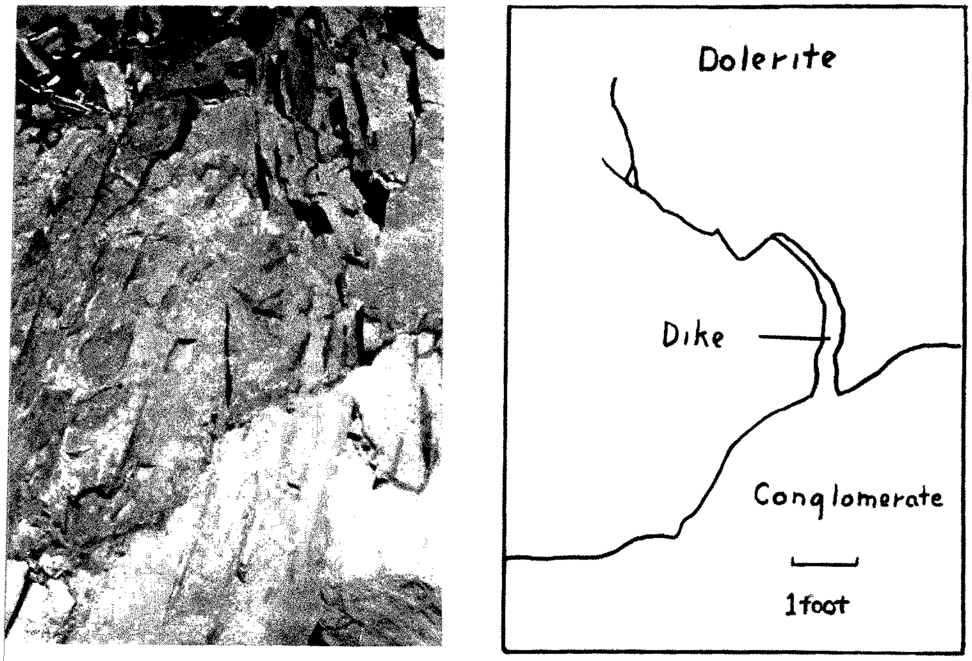

Figure 2. Clastic dike in dolerite. The dike emerges from the underlying conglomerate near the crest of a slight upward bulge in the contact and cuts irregularly and diagonally across the columnar jointing in the dolerite. Vertical scale is much foreshortened by the angle of the picture. The total length of the dike as seen in this picture is about 30 feet.

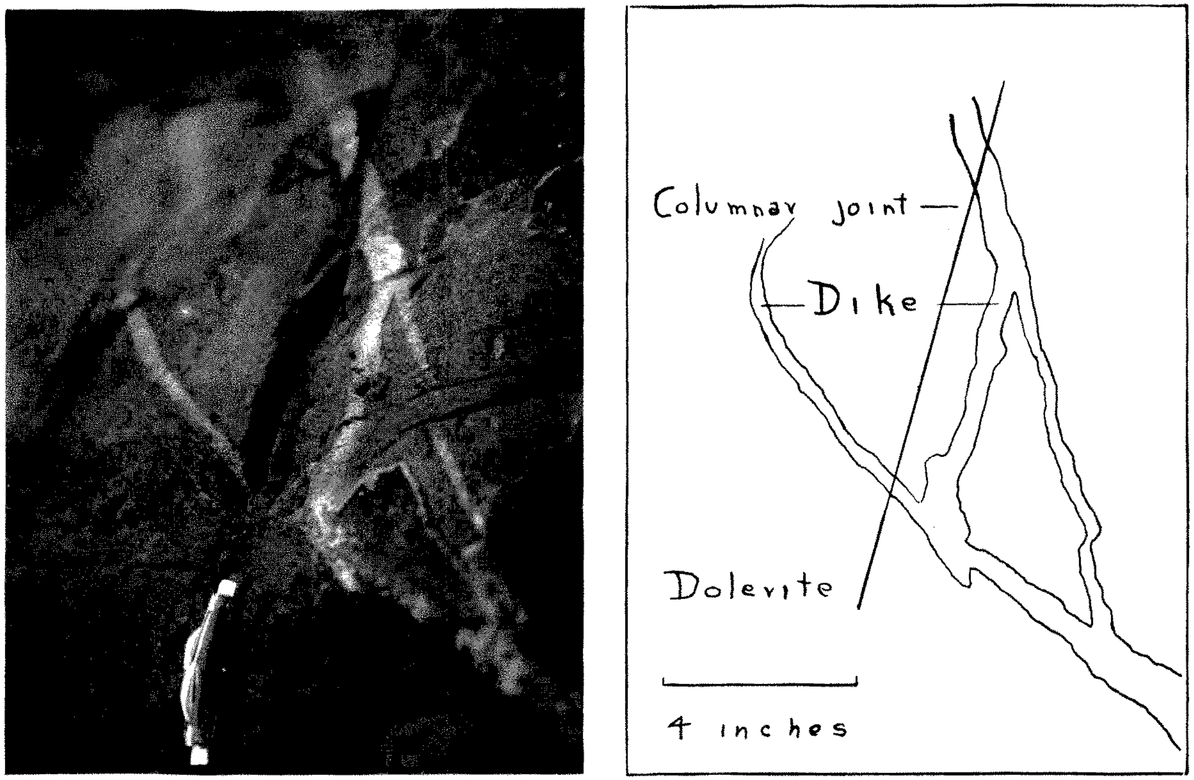

Figure 3. Clastic dike in dolerite about 8 feet above its lower termination in the underlying conglomerate from which it was derived. Note the split in the dike around an angular dolerite inclusion and the relationship to the columnar jointing, indicating that the dike is older than the jointing.

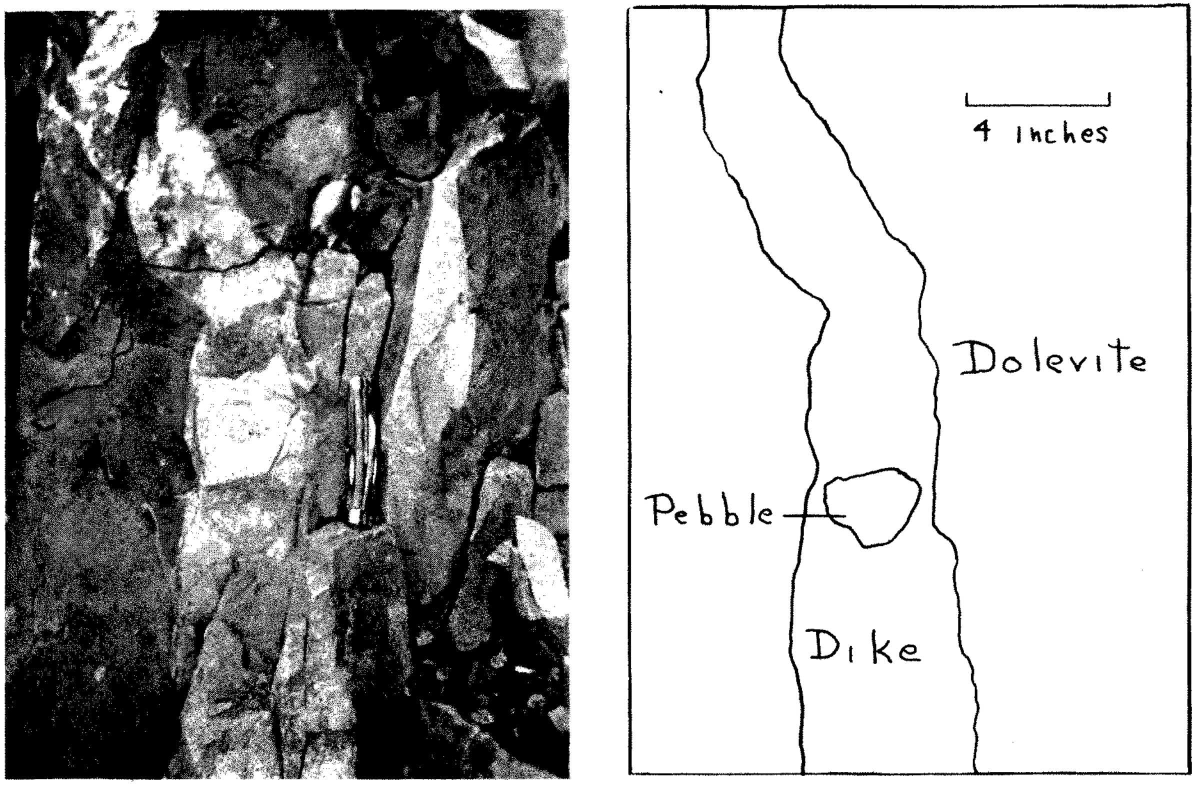

Figure 4. Clastic dike in dolerite 26 inches above its lower termination in the underlying conglomerate from which it was derived. Note the pebble nearly as large as the width of the dike at this point.

Dana. The (111), (201) and (100) faces were almost equally developed, giving the crystal a flattened, pseudo-tetragonal, bi-pyramidal habit. Indices of refraction were greater than 1.85, biaxial, with moderate 2V.

METHOD OF ORIGIN

The field relations and petrologic data supplied by this relatively minor feature throw light on the physical conditions prevailing at an early stage in the final consolidation of this large dolerite sill. Some of the conclusions may have a wider application. The following points are clear:

1. *The dike is intrusive into the sill.* The branching, irregular form of the dike precludes its being a thin, elongate inclusion in the dolerite which floated into its present position while remaining hinged to the underlying conglomerate with which it is continuous. The dike contains inclusions of dolerite.

2. *The material injected into the sill was largely in the solid state.* In fact it was granular material without especially plastic properties. The occurrence proves beyond question that under the proper physical conditions loose aggregates of solid material can be injected in a manner entirely similar in final effect to fluid injection.

3. *The injection took place at a very early stage in the final solidification of the dolerite while the dolerite was still quite hot.* This is shown by the fact that the dike is earlier than the columnar jointing in the dolerite; by the healing of a minor plane of slippage in the dolerite which offsets the dike 2 inches; by the progressively more abundant crystallization of secondary quartz and the growth of secondary minerals such as epidote, sphene, chlorite, pyrite, garnet, and calcite in the dike passing inward from the base of the sill; by the tight "welded" contacts between the dike and the sill; by the hydrolytic alteration of the pyroxene of the dolerite near the dike, and by the presence as inclusions in the dike of minerals from the dolerite.

The geologic relations support the following additional conclusion: *the potential required to produce the injection was not simply due to superincumbent load or differential mechanical stress.* This is shown by the fact that dikes of this character are not found in later fractures in the dolerite, or indeed very commonly in other masses of similar nature which have

been subjected to much greater mechanical stress. The simple sill-like form of the intrusive and the general tectonic history of the area indicates that the stresses present were largely gravitational and hydrostatic. In other words, the fracturing of the dolerite under a heavy superincumbent load and such tectonic stresses as were present is not sufficient to explain the filling of the fracture with solid detrital material injected from the conglomerate bed below. If this were a sufficient explanation, dikes of this character should be quite common instead of relatively rare, and injection of this type should take place when the injected body is cold as well as hot.

This leads to the conclusion that the only sufficient force available was either the vapor pressure of water trapped in water-bearing sediments beneath the sill and heated by the overlying intrusive, or artesian water pressure. However, the presence of mineralized cavities in the dike and the absence of similar dikes in later fractures indicates that the pressure of heated water is the more likely explanation. The dike is located near the crest of an upward bulge in the lower contact of the sill. The sediment involved is coarse, gritty, and conglomerate—a suitable aquifier.

The intrusion is believed to have taken place in the following manner: A short time after the intrusion solidified to the point where it was capable of fracturing like a brittle solid in response to sudden stress, some movement, possibly related to the abrupt offset in the sill floor a few feet from the dike, caused a fracture in the sill. The resulting dilatation caused a local fall in pressure (Mead, 1925, p. 691). The response was a sudden, if not explosive, expansion of the water vapor or liquid water present in the adjacent conglomerate. This brought the solid material in the conglomerate into a momentary state of suspension and it was swept into the fracture as a suspensoid in the inrushing water or water vapor. In other words, the opening fracture was in effect a void that "sucked" up the underlying material which possessed a high elastic potential by virtue of the compressed fluid in its pore space.

The theory that the dike was injected as a plastic mass under external pressure or as an internally lubricated aggregate under external pressure is refuted: first, by the character of the material; secondly, by the jagged, angular character

of the fracture it fills; and thirdly, by the absence of flow textures, mineral alignment, crushing, strain, granulation, and evidence of shear in the dike. Mead (1925, p. 688) has shown experimentally that, "Sand either wet or dry, under relatively slight containing pressures, behaves essentially as a solid and, when deformed, fails largely by fracture along shear planes." He refers here to loose, uncemented aggregates. The presence of an appreciable volume of secondary filled cavities which must have been voids when the dike formed indicates, on the contrary, that the material underwent expansion during injection, rather than compression. The voids are believed to be the direct result of the expansion of water or water vapor during the process of injection outlined, and are direct evidence in support of a mechanism involving reaction of the material under its own elastic potential.

Direct evidence indicating an upper limit of temperature for the intrusion is afforded by the habit of the secondary quartz. The prismatic form with positive and negative rhombohedral termination indicates that it formed as low-quartz below about 575°C. The temperature may have been higher if the quartz did not begin to crystallize until after an appreciable cooling period. It seems more likely that quartz began to form at the time of the injection, perhaps brought on by the pressure drop that has been postulated. The greater abundance of secondary quartz as the dike is followed into the sill supports this supposition.

A lower limit of temperature cannot be fixed with similar probability; however, the suite of minerals forming in the cavities in the dike, in approximately the following order:—quartz, epidote, sphene, garnet, pyrite, chlorite, and finally calcite—is at least suggestive of hydrothermal conditions, beginning at a relatively high temperature. The increase upward in the proportion of sericite as against kaolin in the altered feldspar in the dike also supports this view. Also, as noted, the dike was intruded at an early stage of solidification of the sill. Apparently, then, the temperature prevailing during the intrusion of the dike was not far below an upper limit of 575°C.

An upper limit for the pressure can also be fixed with considerable assurance. The sill appears to have been emplaced beneath at least a mile of rock (Longwell, 1932, p. 81) al-

though it is possible that the overlying strata were much thicker. A depth of 6,000 feet gives a superincumbent load of about 400 bars. The actual pressure of water may have had any value up to 400 bars (more if the overlying rock had containing strength), depending on the temperature, the resistance of the overlying rock to the escape of water or water vapor, and the extent to which the pore space in the rock was saturated with water.

The resistance of the overlying rock to the passage of water from below was probably great. The systematic joints in the sill had not yet formed, and the fracture that the dike fills is believed to be one of the first fractures formed in the solidifying mass. Therefore, the sill was probably a vapor-tight seal. There is also much shale in the Triassic section which is probably fairly impervious. A potential confining pressure at least equivalent to the weight of overlying rock, or about 400 bars, was probably effective. However, the full confining pressure may not have been attained by the water in the underlying sediments because the ratio of water content to available pore space may not have been great enough to bring the water pressure up to the full amount of the available confining pressure at the temperature prevailing.

The critical temperature of water is 374°C. and its critical pressure is about 221 bars; so that the following states of water are possible:

Case	*Relative Temperature*	*Relative Pressure*	*Phases of Water Present*
1.	Below critical temp.	Below vapor pressure	All vapor
2.	" " "	Equal to vapor "	Liquid plus vapor
3.	" " "	Above vapor "	All liquid
4.	Above " "	Below critical "	All vapor
5.	" " "	Equal to " "	All vapor, density approaches liquid.
6.	" " "	Above " "	Supercritical vapor, high density.

The last case would be most favorable for the injection of solid material in momentary suspension. For example, if the temperature were 400°C. and the pressure 400 atmospheres, the specific volume of water would be 1.9 cm.^{3}/gm. (Goranson, 1942, pp. 205-212) and its density 0.53 gm./cm.^{3} The greater the density of the fluid medium, the less the pressure differential and velocity of the fluid need be to produce a given amount of

movement of suspended material. If the temperature of the water in the sediments were below the critical temperature, the most favorable state would be case 3 where the water is in the liquid state entirely. For example, if the temperature were 350°C. and the pressure 350 atmospheres, the specific volume of liquid water would be 1.52 $cm.^3/gm.$ and its density 0.66 $gm./cm.^3$ Thus the density of the fluid medium is the same order of magnitude whether the fluid is liquid or gas as long as the fluid pressure is greater than either the vapor pressure or the critical pressure, as the case may be. Geologic evidence indicates that the pressure was very probably well above the critical value.

The pressure differential resulting from the opening of a fracture such as that filled by the dike is difficult to estimate as its value is not constant but a function of the rate at which the fracture opened, the back pressure of vapor exerted by the vapor concentration in the igneous rock, the velocity of the material rushing into the fracture, and the area over which the fluid expansion was effective. If the fracture was essentially a void as it opened, the initial pressure differential would be approximately the fluid pressure present in the underlying sediments. And if the volume over which the reaction to this pressure differential was effective was large in proportion to the volume of the fracture, the drop in pressure differential would be small. The drop in pressure differential would be further reduced by the rate at which the overlying load settled in response to the upwelling of sedimentary material. Under these conditions the opening crack would in effect suck up the underlying sediments. The geologic evidence indicates that these conditions prevailed.

Figure 5 shows the relation between pressure and density of water vapor at a temperature of 400°C. and also shows the percentage of total volume increase that would result from the expansion of water vapor in a rock with 10 percent initial porosity starting at an initial pressure of 400 bars and temperature of 400°C. Adiabatic effects have been neglected. These conditions are well within the range of probability for the present case. The estimate of initial porosity is probably quite conservative in view of the character of the sediment involved. It can be seen that a pressure drop of 100

bars would produce a bulk volume increase of a little more than 6 percent, and that further drop in pressure would cause a very rapid increase in volume far beyond that required to cause the dike injection. A minimum measure of the actual increase in volume undergone by the dike amounting to 3.5 percent has been given by the measurement of the volume of visible cavities in the rock resulting from gas expansion. This expansion could be effected by a pressure differential of 85 bars, and a drop of an additional 18 bars would double this percentage expansion. These rough cal-

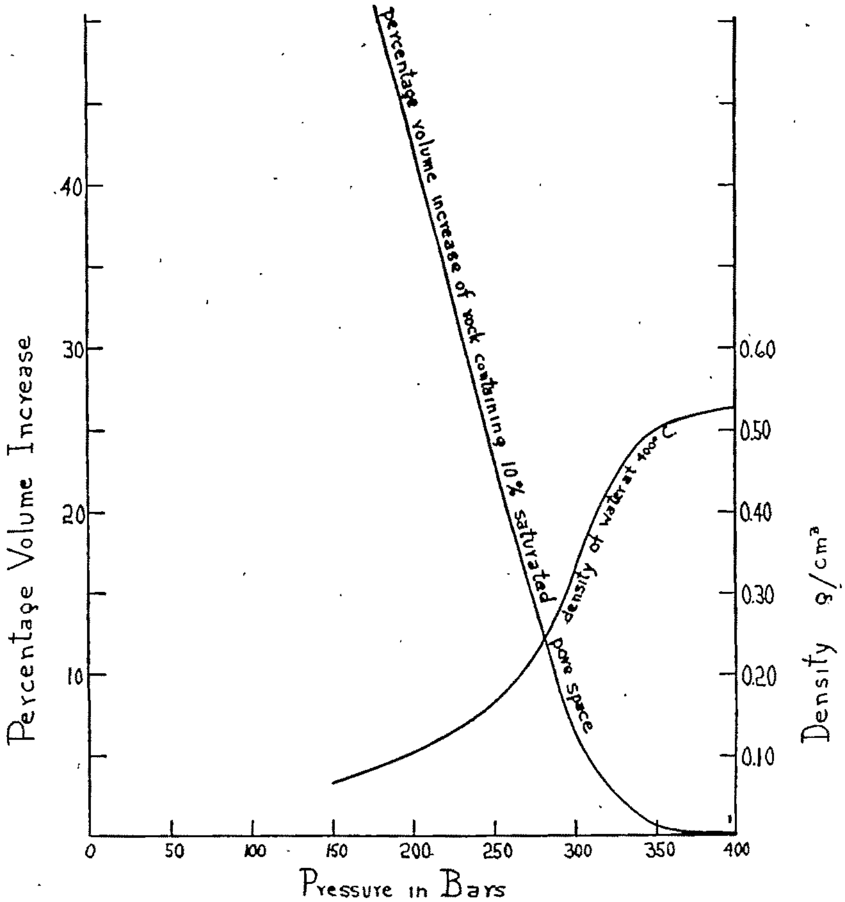

Figure 5. The percentage of volume increase with falling pressure of a body containing 10% pore space filled with supercritical water at a constant temperature of 400° C. and an initial pressure of 400 bars. The density of water at the same temperature and pressures is also shown. (Computed from data by R. W. Goranson, Birch, et al., 1942).

culations show that the opening of the crack need not have produced the maximum theoretical pressure differential in order to cause the effects observed.

DISCUSSION

If the dike originated in the way described, an interesting conclusion can be drawn concerning the vapor pressure of the igneous rock mass. For the proposed mechanism to be effective, the igneous mass at the very earliest stage of consolidation must have had an effective vapor pressure of water well below the external pressure. This leaves the following alternatives:

1. The magma, in solidifying, exuded or used up all its primary water at a relatively high temperature so that at the temperature of final consolidation it was not in equilibrium with a vapor pressure of magmatic water appropriate to the prevailing temperature and pressure. In other words the dolerite was relatively dry at a late stage; or
2. The water or vapor was held by the rock at this stage in such a way that it could be given up at only a relatively slow rate in response to a fall in external pressure.

The hydration of the igneous rock along the contacts of the dike with the dolerite suggests that the dolerite was relatively dry, and that at the stage in which the clastic injection took place the igneous mass was actually capable of using up water, if available, at the prevailing external pressure. Thus the chloritization which is prevalent in the columnar cooling joints of the mass may have resulted from the influx of external water or water vapor as these joints opened. On the other hand, the secondary chlorite present in the dike requires the addition of magnesia to the sedimentary material and this must have been supplied by emanation in some form from the dolerite. An interchange between two masses not in chemical equilibrium at the prevailing pressure and temperature is indicated.

The rather remarkable suite of minerals in cavities in the dike, including sphene, epidote, garnet, pyrite, chlorite, quartz, and calcite, leads to speculation as to the conditions under which the transport and recrystallization of chemical constituents took place. The evidence points to the dike having been pervaded by super-critical water vapor, but also indicates that no continued flow of water or vapor took place after the initial injection. The dike appears to terminate upward, and

though lateral flow is not precluded, nothing in the dike or the geologic surroundings indicates that flowage of vapor or solutions was effective. This strongly suggests that transport and recrystallization of mineral components took place in part at least by diffusion through a supercritical vapor.

Bowen and Tuttle (1949, pp. 441, 444) have recently shown experimentally that very appreciable transportation of silica takes place in super-critical water vapor. This transportation is ascribed by Bowen and Tuttle to "convective circulation" of vapor, but it is described as having taken place through capillary tubes and around tightly fitting crucible covers (Bowen and Tuttle, 1949, p. 441). The question may be raised as to whether the process was convection or diffusion under these conditions.

Even if the equilibrium concentration of a substance in a solution is very low, if it is removed in one part of the system as fast as it goes into solution in another part, the amount of transportation depends on the rate of diffusion as well as the equilibrium concentration. The cyanide process for dissolving and reprecipitating gold is to a certain extent a case in point. The rate of diffusion in a super-critical vapor is much higher than in liquid solutions, and although the concentration of a substance may be very low at any given instant, it may migrate through the vapor at a rapid rate.

The time during which relatively high temperatures permitted the formation of secondary minerals in the clastic dike was probably on the order of a few months or years, and the presence of the secondary minerals may be explained by the diffusion of the added components through super-critical water vapor. This occurrence points up the importance that the state and conditions of external as well as magmatic water may play in the process of contact metamorphism (Knopf, 1936, p. 174).

There are many accounts of clastic dikes in the literature. No attempt has been made by the present authors to survey this subject completely. However, Newsom (1903) has summarized a considerable portion of the literature prior to 1903 and in addition has described some very striking clastic dikes in several localities in California, most of which dwarf the dike that is the subject of this paper. Shrock (1948, pp. 212-221) describes many types of clastic dikes and cites numerous examples. Most of the clastic dikes and other dis-

cordant clastic masses described or referred to by Newsom and Shrock are of sedimentary origin and cut other sedimentary rocks. The geologic evidence is clear that many discordant masses have originated by material filling open fissures from above or being let down into solution cavities in limestones and of course these are irrelevant to the present discussion. However, Newsom and Shrock cite abundant evidence to show that clastic dikes are formed commonly by injection from below, and are commonly composed of sand or coarser material which is injected into finer grained sediments, such as shale. Furthermore, in a large proportion the material of the dikes is slightly to highly bituminous. However, dikes of clay are not rare.

Newsom (1903, p. 268) summarizes the methods of formation, and states in regard to the origin of clastic dikes injected from below that, "If the authors are correct in their deductions [this type of clastic dike has been formed]: by injection of material from below along with water, petroleum or petroleum residues. The injection has been due to hydrostatic pressure, pressure from overlying beds, pressure from gas, or from combinations of these." Newsom states in conclusion, ". . . conditions favorable to the formation of clastic dikes by intrusion are produced when any unsolidified sedimentary deposit, be it sand, clay, or calcareous material, is covered by a later deposit of any kind which solidifies before the solidification of the underlying sediments. Under such conditions the entrapped unsolidified sediments may be forced into joints or fissures in the enclosing hardened rocks, should such fissures be formed. Clastic dikes may also be produced by the pressure of overlying strata squeezing soft unresisting rocks, such as shales, into cracks in either overlying or underlying rocks which have a greater crushing strength than the entrapped beds."

Little fault can be found with this admirable statement, and indeed subsequent investigations of clastic dikes that have come to the authors' attention have added little to it. However, the statement as it stands does not convey a true insight into the intrusive mechanism that appears to have been effective in emplacing the dike described in this paper; nor does Shrock's (1948, p. 213) statement that "Clastic materials, if they contain enough water or petroleum to have the property of a fluid, can be injected from below into a fractured

formation if there is sufficient pressure." The primary force responsible for the injection is an elastic potential possessed by the material itself because it is saturated with a fluid medium, liquid or gaseous, capable of expansion due to its own internal pressure, so that the material as a whole responds to any local fall in external pressure such as that resulting from the dilation of enclosing rocks as a result of fracturing. It is not external pressure that forces the material into place in a plastic or fluid manner. Indeed, in a large number of cases described, with the exception of clay dikes in coal, etc., whose plastic origin is not questioned, the intrusive material is less plastic than the rocks that it intrudes.

Published descriptions of clastic dikes lead to the conclusion that the mechanism described in this paper may be perhaps the major cause of clastic intrusions. The elastic potential need not be supplied by heat. Strong artesian pressure or natural gas pressure may be equally effective. Many dikes have been attributed to the upward flow of artesian water, and on occasions as in the Charleston, South Carolina, and New Madrid, Missouri, earthquakes (Dutton, 1889, pp. 284-302), (Fuller, 1912, pp. 1-119), sand and water have actually spurted from fissures at the surface. Where there is an actual flow of artesian water it may be expected to transport and deposit material. However, the simple flow of artesian water does not explain the many instances where dikes are seen or are inferred to terminate upward so that no thoroughgoing flow was possible. The effective mechanism in these cases is inferred to be an elastic response to a fall in local pressure due to an opening void, the solid material being transported as a suspensoid in the fluid medium. Liquid water at the pressures and temperatures prevailing under simple artesian conditions, being virtually incompressible and thus inelastic, could produce such dikes only where the water in the surrounding sediments can respond to a local fall in pressure by an abrupt influx toward the low pressure area.

A large number of clastic dikes that have been observed, in fact many of the largest and most striking ones, are in petroleum-producing areas and they are commonly impregnated with bituminous material. This strongly suggests that natural gas and petroleum supplied the necessary elastic medium. Meek (1928) describes a sandstone dike about a foot in width

and exposed vertically for 50 feet. The dike is composed of sand impregnated with tar cutting a Miocene shale. Heavy mineral analysis proves that the dike was derived from sands more than 1,000 feet stratigraphically below the shale. Meek advances as the most probable explanation, ". . . during a severe earthquake shock, or while the beds were being warped or folded, a fracture could have been developed, into which soft, incoherent, and perhaps water-soaked sand was forced, or injected, from some source lower in the section, by virtue of the compressional forces which were operative during such a condition of exceptional earth stress." (Meek, 1928, p. 275) This interpretation of the relative physical behavior of sand and shale under stress is at variance with the properties of these materials. The case described by Meek seems more readily explainable by the mechanism proposed in this paper, with petroleum gas pressure, for which he gives abundant evidence, supplying the elastic medium.

The general opinion concerning the origin of clastic dikes is probably expressed by Grout (1932, p. 325) who states, "Clastic dikes are said to be derived generally from lower formations and to be pressed up by the weight of the rock load or by gas pressure. The sand grains of dikes are well rounded and were no doubt lubricated by some fluid while being injected." Clastic dikes are also commonly cited as demonstrating the plastic behavior under stress of decidedly non-plastic material. In the opinion of the authors these views involve a misconception of the mechanical role of confining pressure, deformational stress, and fluid medium in many typical cases of clastic injection. The phenomenon is elastic rather than plastic.

APPLICATIONS TO ERUPTIVE ROCKS

In many eruptive rock complexes, bodies are found with intrusive relations to associated rocks, where the seemingly intrusive bodies appear to be granular aggregates of the earliest forming constituents of the eruptive mass. Examples may be found among the so-called magmatic ore deposits of chromite, magnetite and ilmenite, late lamprophyric dikes in granite masses, and small monomineral intrusions of anorthosite and dunite. Somewhat improbable mechanisms such as the sinking and remelting or resolution of early crystals to form a

magma capable of re-injection have been proposed (Beyschlag, Vogt and Krusch, 1914, p. 243; Hess, 1938). Other workers have doubted that many of the monomineral ore deposits thought to be magmatic are accumulations of early crystalline differentiates (Lindgren, 1913, p. 749; Broderick, 1917, pp. 691-693; Osborne, 1928, pp. 780-782), but if any bona fide examples do exist it may be possible to explain their anomalous intrusive nature by the mechanism outlined in this paper. If an aggregate formed by crystal settling it would surely have a relatively large amount of pore space, because the density difference between crystals and magma required to produce a closely packed aggregate is small. This pore space would certainly be filled with the magma in which the crystals settled, and this magma would probably contain dissolved volatiles and possess appreciable vapor pressure. After the overlying portion of the magma chamber solidified, this interstitial magma might remain liquid because held interstitially in the lowest and hottest portion of the mass. Any fracturing of the overlying mass would set in motion the mechanism that produced the altogether intrusive injection of sand and gravel here described. Thus the categorical statements commonly made that solid crystals cannot be injected may have to be modified.

Reactions between the interstitial magma that provided the elastic medium, the wall rocks of presumably more silicic and alkalic composition, and the early formed crystals themselves, injected into a cooler and lower pressure environment, may explain the contact effects and replacement textures observed in many cases. A considerable degree of recrystallization and contact alteration has been shown in the case of the simple clastic dike described in this paper.

Such seemingly anomalous phenomena as the mica-peridotites that are occasionally found cutting flat-lying, undeformed sediments, even stratified salt deposits, without appreciable contact alteration (Maynard and Ploger, 1945; Filmer, 1937, 1940), may be intruded in the manner suggested; and the mechanism may, of course, be effective in helping to bring major intrusions from a lower to a higher level in the earth's crust.

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ON A DISTINCTION BETWEEN LATE-MAGMATIC AND POST-MAGMATIC REPLACEMENT REACTIONS

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ABSTRACT. The kinds and habits of the minerals involved having failed to provide reliable criteria for discriminating between late- and post-magmatic replacements, it is suggested that more attention should be paid to the distribution of the products of these replacements through the rock mass. If a replacement reaction occurred while the magmatic residue was still homogeneously distributed through the mass, the amount of replacement mineral formed would be roughly proportional to the amount of original mineral available and probably would not vary inversely with the quantity of the latter surviving the reaction. If the reaction occurred after separation of magmatic residues from solid rock was well underway. the amount of replacement mineral would be essentially independent of the amount of original mineral but would vary inversely with that part of the original mineral surviving the reaction. On this basis it is shown that evidence gained from a sample consisting of 21 specimens offers reasonable assurance that muscovite pseudomorphously replacing plagioclase in the granite of Barre, Vermont, is late-magmatic rather than post-magmatic or hydrothermal.

SOME QUESTIONS OF TERMINOLOGY

THE descriptive terminology of end-stage reactions has been developed and refined to such an extent as to render it nearly worthless for an argument of this type. Each descriptive term has many connotations and each natural phenomenon may be described by any of several terms. On the other hand, the genetic terminology that enjoyed such great vogue in recent years is so abstract as to be inapplicable in most practical situations.

An argument that is to be carried through with small samples—a characteristic unfortunately shared by most geological disputes—requires some *a priori* hypothesis or model, for with small samples all we can ever hope to do is determine the compatibility of the observations with the hypothesis. Now in general the only useful hypotheses are those which may be either confirmed or rejected by the observations they are created to explain, and to reach such hypotheses clear and unambiguous descriptive terminology is essential. The matter is of such importance I have thought it best to clutter up the literature with yet one more discussion of terms before getting down to business.

In this note little will be said about the state of the materials involved for the very good reason that I have never visited an active magma in its chamber. I am guilty of the assumption that there is a (granite) magma and that it consists of a mixture of crystals and liquid, for it is in this way that I have been able to make the most sense of the observations. This is perhaps partly a personal idiosyncrasy. The data are given in full in table 1, and those who find it easier, more useful, or more fashionable to think in terms of alkali-emanations, "clouds of ions," or wholesale metasomatism may make full use of them.

The reader is entitled, however, to some rationalization of the discrimination made here between late-magmatic, post-magmatic, and hydrothermal action. The magmatic residue that never separates from the crystallized portion of the magma may be mostly water and will likely be pretty hot, but so long as it shows no detectable tendency to concentrate within or escape from the magma chamber, remaining, so far as we can tell, disseminated through the rock, I regard it as part of the magma, and the products of reaction between it and the solid part of the magma as late-magmatic. If for some reason—any number may be imagined—there is a tendency for residual liquors to be expelled from some parts of the chamber and gather in others without formation (or preservation) of well-defined fractures, the distribution of the products of end-stage replacement reactions through the mass will be very different from that found for the magmatic case. It is possible, but unproved, that deuteric action belongs in this category. At any rate, magma in the sense of a homogeneous paste of solids and liquids has ceased to exist at this stage; for lack of a better name reactions occurring at this time are here called post-magmatic. Anticipating considerable objection, I have reserved the term "hydrothermal" for the products of reactions in which some at least of the reagents seem to have reached their present sites by means of fractures and openings in the rock. Certainly such fracture fillings may give rise to metasomatic replacement along their margins; but if there is no evidence that material has been introduced very little is gained by the assertion that it has. This amounts to no more than saying that metasomatic replacement of one common mineral by another common mineral is not of itself evidence of the introduction of hot waters of foreign origin.

All that is new in this note is based on the notion of pseudomorphous replacement. The Mu_1 values of table 1 report the muscovite in each slide occupying space that seems once to have been filled by plagioclase. For the most part the basis of the inference is quite clear, since muscovite crystals are usually much smaller than plagioclase crystals and commonly lie either entirely inside or entirely outside them. Not infrequently, however, large flakes of white mica are interbanded with biotite and these may continue without visible break into adjacent plagioclase. In the plagioclase they tend to form irregularly bounded poikilitic plates or vermicular intergrowths, and the few cases of really extensive replacement are almost all of this type. There is an element of judgment involved in deciding which parts of such a muscovite grain fall in Mu_1 and which in Mu_3. I believe that most petrographers would have made about the same decisions I did and that though this uncertainty in identification must contribute to the analytical error, and hence to the residual variance, its contribution is quite small. Probably more of the analytical error is traceable to the minute size of many of the muscovite flakes.

Finally, in arguments of this type purely petrographic considerations rarely lead to satisfactory materials balances or stoichiometric equations, and the present case is no exception. On the assumption that "muscovite" is really potash mica, or even if it is pyrophyllite, its replacement of sodic oligoclase must release a certain amount of soda, lime, and silica. The lime may have gone into carbonate, which is present in about the right amount. The fate of the silica and soda is unknown. If country rock outcrop were more abundant, it might be useful to look for them there, but every explanation of this particular replacement runs into the same difficulty. Whether the released materials end up in the country rock or in the ocean is of small moment in determining whether the replacement was late-magmatic, post-magmatic, or hydrothermal.

OUTLINE OF THE PROBLEM

All of us who still believe in magmas are required also to imagine the end stages of plutonic magma consolidation. On the assumption that the magma contains more water than the rock, we must suppose that a hydrous residue remains after

most of the magma has crystallized, that the residue—or some derivative of it—does finally leave the magma chamber, whether by boiling or filtration, and that immediately before and during the early stages of the separation it is widely disseminated through the mass.

Even conceptually, however, reactions taking place in a largely solidified magma with only a thin interstitial liquid can hardly be distinguished from those taking place after the magma as such has ceased to exist. In practical cases this distinction usually depends on the geologist who happens to be making it. Traditionally, attempts to provide some reasonably objective basis for it have centered on the kinds and habits of the minerals involved. The history of the subject has been excellently summarized by S. J. Shand (1944, 1948) who has managed to cut back the dense verbiage that had grown up over it. It is to be hoped that this operation will be repeated at frequent intervals, though it seems a little unfair to expect one man to do all our pruning for us. As Shand's latest discussion shows (1948, p. 158), the nub of the difficulty is that neither the kind nor the habit of a mineral leads to a grouping in which the classes "late-magmatic" and "post-magmatic" are mutually exclusive.

The criteria currently in use may be applied quite independently of the distribution of the allegedly late- or post-magmatic minerals through the rock, yet it is just this distribution that seems to offer the most direct entry to the problem. If a mineral occurs in about the same amount everywhere in a rock mass, it must be the product of magmatic action or of very thorough metamorphism or weathering. If these last two can be excluded, we have no choice but to regard it as magmatic. If, on the other hand, it occurs only, or primarily, in veins or fracture fillings, it is clearly hydrothermal (though neither the heat nor the water is *ipso facto* of magmatic or non-magmatic origin). We can distinguish yet a third case in which there may be a decided tendency toward local enrichment or depletion so that the mineral is sporadically and irregularly distributed through the mass yet is apparently not concentrated along fractures or veinlets. Where magmatic residues are expelled by filter-pressing, local concentrations must often precede the actual expulsion and might easily lead to the sparsity or virtual absence of

the products of end-stage reactions in some parts of the mass and their considerable enrichment in others. If sufficient modal data were available, it would be useful to inquire to what extent the distribution of minerals regarded on other grounds as deuteric is of this type.

In the absence of data it may at least be pointed out that two pre-hydrothermal stages could be distinguished in this fashion and that regardless of what name be applied to the second, or "sporadic" type, the first can hardly be considered other than late-magmatic. If the reactions involved in both cases are pseudomorphous replacements, it may be shown that very different relations would hold between the reaction pairs depending on the distribution of reagents through the rock during the reaction.

If we suppose first that conditions favoring a particular reaction terminate before there has been any significant differential concentration (in space) of magmatic residues, so that during the critical period the entire rock is exposed to their action, the amount of replacement product (R) formed will be directly proportional to the amount of original mineral (O) available. There will be positive correlation between O and R and the significance of the sample correlation may be tested by the usual nul hypothesis. The best estimate of the proportionality will be the coefficient of regression of R on O, but it is not likely to be a very good one unless the sample is rather large and the environment quite uniform.

If, on the other hand, the reaction does not get underway until the magmatic residues have begun to concentrate, the amount of R formed will be a function not of O[1] but of the time during which the O contained in some particular sample, whatever its amount, was exposed to materials capable of reacting with it to form R. Assuming an abundant supply of these, so that in any particular case the reaction *might* proceed to completion, R would be absent from some parts of the rock, present in some, and abundant in others, but its amount would be essentially independent of that of O. Under such circumstances there would have to be negative correlation between R and the quantity (O-R), the amount of original mineral surviving the reaction. In the next section some analy-

[1] Except in the sense that $R < O$. O is here taken as a major constituent abundant throughout the rock, while R is in general a minor constituent.

tical basis for these assertions is given and the succeeding section describes a practical illustration.

CORRELATION OF A SUM WITH ONE OF ITS PARTS

A better treatment of the relations described below through equation (4) may be found in either of two excellent elementary statistics texts (Snedecor, 1946; Yule, 1946). The discussion is included here so that the argument may be followed, if necessary, without outside reference.

Let x be the deviation of a single measurement from the group mean, $(X - \bar{x})$, n be the number of measurements, and represent different variables by subscripts. Then the standard deviation is $s = \sqrt{\frac{S(x^2)}{n-1}}$, and the product moment correlation coefficient is $r = \frac{S(x_1x_2)}{(n-1)s_1s_2}$, where large S signifies summation. If $X_3 = X_1 + X_2$, then by definition,

$$x_3 = x_1 + x_2. \tag{1}$$

Squaring, summing, and dividing each summed term by $n-1$ gives

$$s_3^2 = s_1^2 + s_2^2 + 2r_{12}s_1s_2 \tag{2}$$

This is the familiar relation used in isolating errors in experimental techniques. Where successive steps may be presumed independent, if, for instance, step 1 is the taking and step 2 the titration of an aliquot, then $r_{12} = 0$ and the third term vanishes.

Further, by definition,

$$r_{13} = \frac{S(x_1x_3)}{(n-1)s_1s_3} = \frac{S(x_1^2) + S(x_1x_2)}{(n-1)s_1s_3} \tag{3}$$

and combining (2) and (3) gives

$$r_{13} = \sqrt{\frac{s_1 + r_{12}s_2}{s_1^2 + s_2^2 + 2r_{12}s_1s_2}} \tag{4}$$

which is the usual statement for the correlation of a sum (X_3) with one of its parts (X_1), as a function of the relation between the parts.

Finally, let X_1 be the amount of R (the replacement product of the preceding section), X_3 be the quantity of O (the original mineral prior to replacement), and X_2 be (O-R) (the amount of O surviving the replacement process). The two types of replacement reaction may then be stated as special cases of

equation (4), but first it will be helpful to restate the equation explicitly for r_{12}, thus:

$$r_{12} = r_{13}\left(\frac{s_3}{s_2}\right) - \frac{s_1}{s_2} \qquad (5)$$

The late-magmatic reaction, in which the amount of replacement product is proportional to the amount of original mineral available for the reaction, is exemplified by $r_{13} \geqslant 0$, and in small samples r_{13} will be rejected by the nul hypothesis test unless it is in fact quite large. Negative values of r_{12} may occur only if $s_1 > r_{13}s_3$; there is no *a priori* reason why this may not be so, but it is not likely that negative values of r_{12} will often be significant. For 19 degrees of freedom, for instance, the .01 point for r is 0.58; correlations smaller than this will usually be rejected as insignificant. Using data from the next section as an example, $s_1 = 1.46$, $s_2 = 2.98$ and $s_3 = 3.59$. Entering equation (5) with these values yields $r_{12} = +0.21$, which offers no support to the suggestion that X_1 and X_2 are negatively correlated. By similar substitution it may be shown that significant values of $r_{13} > 0$ and $r_{12} < 0$ could not occur together in this case unless $s_1 \geqslant 3.52$, a value more than twice as large as that actually observed. I believe this is a fairly typical example and that in general if r_{13} is significantly positive r_{12} will not be significantly negative, though this is to be regarded as a likely rather than a necessary result.

In the second type of reaction, which does not start until the concentration of magmatic residues is well underway, the extent of replacement will be governed largely by the time during which any part of the rock is exposed to their action. R and O will be independent except for the mild restriction that $R \leqslant O$. (In the example described below, R is never more than a fourth of O. The restriction might be bothersome in the case of very extensive replacement, such as often occurs in the metamorphism of gabbroic rocks.)

From equation (5)

$$\lim_{r_{13} \to 0} r_{12} = -\frac{s_1}{s_2} \qquad (6)$$

so that in this sporadic type of replacement there will be negative correlation between R and (O-R), and if we are confined to small samples we shall again require a rather high sample correlation before discarding the nul hypothesis. As a

correlary of equation (7), if $r_{13} = 0$, $s_1 \leqslant s_2$; but s_1 will probably be a good deal larger in relation to s_2 than in the previous case for the reason that X_1 will be entirely lacking in some parts of the rock and quite abundant in others. This enlargement of range will very likely increase sample variance and tend to generate rather large (negative) values of r_{12}.

These results may be summarized as follows:

Distribution Type	*Corr. of O with R*	*Corr. of (O-R) with R*
I. Homogenous (late-magmatic)	positive	large negative values unlikely
II. Sporadic (deuteric?)	negligible	large negative values likely

The mere fact that the sample statistics of two minerals fall in one of the groups shown in the table is of course no basis for inferring a replacement relation between them; but if the existence of a replacement relation may be inferred *on other grounds* the table offers a method of determining its type. Extra-statistical information is crucial for the reason that the sum of *any* set of paired values will show correlation with either or both members of the pair. In general, if $r_{12} = 0$, $r_{13} = \sqrt{\dfrac{s_1}{s_1^2 + s_2^2}}$, which is always positive. Mineral pairs having no relation whatever to each other will thus frequently appear to fall in type 1. The same would likely be true of sets of numbers drawn from a telephone book or from a table of random numbers.

Where there is no outside information about the relationship between two minerals, it is probably legitimate to dismiss correlation between either of them and their sum as a function of their variances. Where there is independent reason for supposing that the variables are related, however, it is quite as legitimate to regard their variances as functions of the covariance required by the hypothesis.

Although the part-whole correlation may easily lead the unwary astray, it offers a simple, direct approach to many problems and is implicit in many others. A high positive correlation between live- and dressed-weight of beef cattle, for instance, would be a matter of considerable importance to the operator of a slaughter house. It would continue to hold his interest even if it should be pointed out to him that in many

cases there was no correlation between dressed-weight and waste. In our case the live-weight is O, the dressed weight is (O-R), and the waste is R.

The convention that end-stage reactions must terminate before or begin after the concentration of magmatic residues gets underway is of course highly arbitrary and has been adopted only to provide entry to the problem. The opposite state of affairs is more likely to obtain, and the probable effect of this will be that in many small samples neither tendency will attain significance. If the reaction were chiefly confined to one period or the other, however, it would generate the appropriate variances and covariances. The size of sample required to detect the effect may be regarded as some gauge of its strength. The next section describes a case in which the late-magmatic character of the reaction appears to have been strong enough so that it may be detected with reasonable assurance even in a rather small sample.

RELATION OF MUSCOVITE AND PLAGIOCLASE IN THE GRANITE OF BARRE, VT.

The granite of Barre is characterized by a rather low quartz content and a considerable excess of plagioclase (sodic oligoclase) over potash feldspar (microcline). Biotite is the principal mafic constituent. Transparent accessories, chiefly apatite, sphene, and epidote, are quite common; opaque minerals are remarkably scarce. Muscovite[2] is abundant throughout, occurring as a pseudomorphous replacement of plagioclase or in close association with biotite. Almost every thin section contains a little carbonate, nearly all of which has apparently replaced plagioclase. Biotite is sometimes transformed to chlorite, which is then commonly rimmed by a minutely crystalline aggregate of very high index and birefringence, probably leucoxene. The Barre is a medium-fine granite; in Shand's classification it is a peraluminous soda granite and in the Johannsen system it would be called granodiorite. Table 1 shows the results of point-counter analysis of twenty-one thin sections. An area ¾″ by 1″ was measured on each slide and the number of points identified for each analysis is shown in the table. Before analysis the slides were etched with HF and stained with sodium cobaltinitrite in the fashion described by Keith (1939).

[2] "White mica" would be a better term if it were less clumsy. Identification has been made by the usual thin section methods which do not distinguish between muscovite, paragonite, and pyrophyllite.

TABLE 1

Point Counter Analysis of 21 Thin Sections of Barre, Vt., Granite

Quarry	Spec. #	Quartz	Microcline	Plagioclase	Biotite	Mu_1*	Mu_2*	Mu_3*	Total Muscovite	Carbonate	Opaque access.	Non-opaque access.	# points counted
I	6	26.6	18.2	38.6	6.3	7.3	0.4	0.8	8.5	0.9	0.1	0.8	1406
	7	31.2	17.6	32.4	9.3	7.1	0.2	0.7	8.0	1.0	0.2	0.3	1350
	8	31.6	17.3	35.2	9.1	4.0	0.0	0.5	4.5	0.1	0.1	2.1	1464
II	9	32.7	20.0	32.1	8.0	4.7	0.0	1.1	5.8	0.4	0.1	0.9	1491
	10	24.7	23.5	32.3	8.5	8.0	0.0	0.9	8.9	1.0	0.0	1.1	1358
	11	22.5	18.7	39.7	7.0	8.8	0.1	0.8	9.7	0.8	0.1	1.5	1415
	12	26.4	23.8	33.5	6.2	6.2	0.1	1.8	8.1	0.6	0.3	1.1	1446
III	14	29.2	21.1	38.9	6.4	7.2	0.0	1.0	8.2	0.5	0.2	0.5	1294
	15	20.8	28.8	38.8	7.9	5.8	0.3	0.8	6.9	0.3	0.1	1.4	1459
	16	30.8	17.7	32.6	9.4	8.0	0.1	0.2	8.3	0.6	0.2	0.4	1341
IV	17	25.1	18.8	36.1	9.4	8.6	0.2	0.6	9.4	0.7	0.1	0.4	1450
	18	24.8	19.7	35.8	9.6	6.8	0.3	1.2	8.3	0.8	0.3	0.7	1483
	20	28.0	15.4	38.3	7.5	8.0	0.1	1.0	9.1	1.1	0.0	0.6	1466
	21	29.0	18.8	33.0	9.1	7.0	0.2	0.9	8.1	0.9	0.2	0.9	1475
V	22	27.4	24.8	36.6	0.2	8.8	0.1	0.9	9.8	0.6	0.1	0.5	1486
	23	25.8	21.2	32.6	7.1	10.3	0.1	0.8	11.2	1.4	0.4	0.3	1427
	24	25.4	20.4	30.3	16.0	6.0	0.4	0.4	6.8	0.4	0.1	0.6	1429
	25	27.9	17.6	37.6	6.3	8.4	0.2	0.7	9.3	0.6	0.1	0.6	1281
	26	28.6	18.5	33.5	7.7	7.7	0.4	1.0	9.1	1.5	0.3	0.8	1480
	27	24.3	18.3	35.9	11.1	7.3	0.2	0.5	8.0	1.4	0.5	0.5	1521
	28	27.9	12.5	40.4	8.7	7.0	0.2	0.7	7.9	1.6	0.4	0.6	1375
Mean		27.2	19.4	35.2	8.1	7.3	0.2	0.8	8.3	0.8	0.2	0.8	1421

* Mu_1 = Muscovite in Plagioclase, Mu_2 = Muscovite in microcline, Mu_3 = other Muscovite, mostly with biotite.

Location of Specimens

I Wells Lamson; 6 from West part of quarry, 7 and 8 from East part, current working.

II Wetmore Morse; 9 from #5 derrick, 10 from #12 derrick, 11 from #6 derrick, 12 from #13 derrick.

III Smith Granite Co; 14 from upper works, near Wetmore Morse, 15 from main central working face, 16 from Southwest part of quarry ("Barre medium-dark").

IV J. K. Pirie Estate Quarry; 17 from Southwest corner of quarry, 18 from center portion of quarry, 20 from Northeast key in floor of quarry, 21 from Northwest floor of quarry.

V Rock of Ages Corp. Quarry; 22 from Gazeley Pit, 23 from main quarry near derrick #10, 24 from black knot in grout near derrick #10 ("Barre dark"), 25 from #9 derrick, 26 from first derrick between office and observation booth, 27 from #8 service derrick, 28 from #5 derrick.

As in most of the finer grained granites of New England there is a tendency for potash feldspar—here exclusively microcline—to mantle plagioclase, but only very rarely is there evidence that these mantles have developed at the expense of plagioclase. Rather, early formed plagioclase crystals, often markedly euhedral, seem to have served as nuclei for the later crystallization of microcline. Many of the microcline crystals lack plagioclase cores and many of the plagioclase crystals show only incomplete microcline rims or none at all, so that probably the formation of microcline began well before that of plagioclase had been completed. Except in the true "dark Barre" (analysis number 25 in table 1), which is now very scarce and seems never to have been abundant, biotite appears to be an early-formed mineral developing before, or at any rate independently of, feldspar.

Muscovite on the other hand conspicuously replaces plagioclase. Commonly it forms plates and lamellae along cleavages. These may spread and interlock, yielding a complex aggregate, or they may coalesce into large poikilitic single crystals. Muscovite sharply interbanded with biotite may spread irregularly into adjacent plagioclase crystals, forming a crude halo about the biotite where it abuts on plagioclase. Really extensive replacements are generally of this type. In such cases the muscovite may be in either poikilitic or vermicular intergrowths with the plagioclase. A little muscovite seems to have been introduced with quartz in minute fractures, and here it often displays toward quartz the same poikilitic habit elsewhere shown with plagioclase. I have never been able to follow one of these veinlets more than a few millimeters and do not believe they account for more than a very small part of the muscovite or quartz contained in the rock. In many thin sections they do not occur at all.

From what has been said it seems fair to regard the great bulk of muscovite as almost certainly pre-hydrothermal and it remains only to decide whether it formed before or after significant separation of magmatic residues from crystalline material in the magma chamber; whether, in the terminology of the first section of this note, muscovite is to be classed as late-magmatic or post-magmatic. As far as I know there is no test that may be applied to *all* of the muscovite. Table 1 shows, however, that about 90 per cent of the Barre mus-

covite occurs as a pseudomorphous replacement of plagioclase, and for this material the method of the preceding section is available.

The original plagioclase available for the reaction (O of section 1) may be reconstructed by summing plagioclase, carbonate, and Mu_1 of table 1. The quantity of O surviving the replacement reaction (O-R) is the sum of plagioclase and carbonate. R of section 1, the replacement mineral, is Mu_1 of table 1. In summary form, the terminology is as follows:

Section 2	*Section 3*	*Section 4*
R	X_1	Mu_1
(O-R)	X_2	$(Pl + C)$
O	$X_3 = X_1 + X_2$	$(Pl + C + Mu_1)$

The relevant values are drawn together in table 2 and shown graphically in figure 1. The correlation of R with O, or r_{13}, is $+ 0.58$. The correlation of (O-R) with R, or r_{12}, is $+ 0.21$. The case thus falls in the first group of section 3 (homogeneous or late-magmatic); r^2_{13} or 33.5 per cent of the sample variance of muscovite occurring as pseudomorphous replacement of plagioclase is compatible with the hypothesis that the replacement reaction occurred before extensive segregation of magmatic residues from crystalline material in the magma chamber.

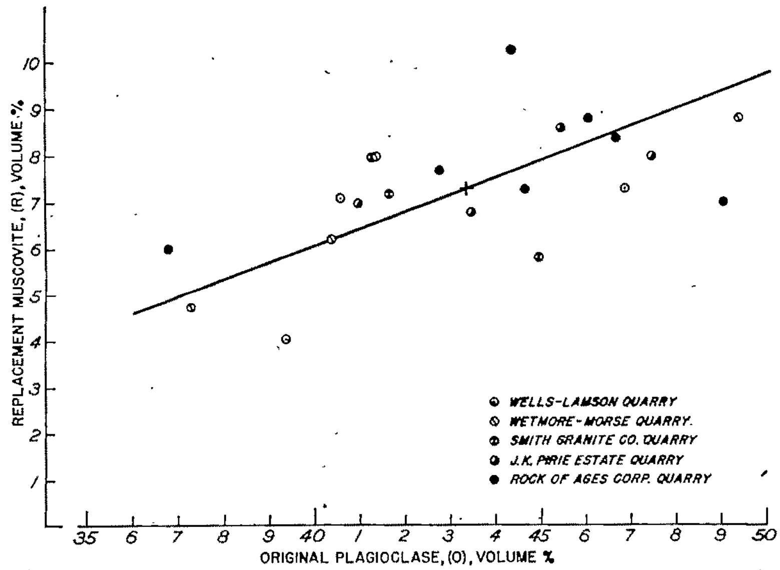

Fig. 1. Replacement muscovite as a function of original plagioclase in the Barre granite (data from Table 1).

TABLE 2

Values of R, O and O-R from Table 1

Specimen No.	O (Mu$_1$ + Pl + Carb.)	R (Mu$_1$)	O–R (Pl + Carb.)
6	46.8	7.3	39.5
7	40.5	7.1	33.4
8	39.3	4.0	35.3
9	37.2	4.7	32.5
10	41.3	8.0	33.3
11	49.3	8.8	40.5
12	40.3	6.2	34.1
14	41.6	7.2	34.4
15	44.9	5.8	39.1
16	41.2	8.0	33.2
17	45.4	8.6	36.8
18	43.4	6.8	36.6
20	47.4	8.0	39.4
21	40.9	7.0	33.9
22	46.0	8.8	37.2
23	44.3	10.3	34.0
24	36.7	6.0	30.7
25	46.6	8.4	38.2
26	42.7	7.7	35.0
27	44.6	7.3	37.3
28	49.0	7.0	42.0
$\bar{x}$	43.3	7.3	36.0
s	3.59	1.46	2.98

The residual variance is of course far too large to be ignored, but the interpretation placed upon it will depend on the detail of the hypothesis being tested. If we are prepared to accept as magmatic only that part of the replacement accounted for by a *single* linear function of O, then the residual variance contains only two components, experimental error and post-magmatic or non-magmatic influences tending to localize the replacement process. This would imply that the regression coefficient of R on O, $b_{13} = r_{13}\frac{s_3}{s_1}$, is an estimate of a single constant supposed to hold for the entire mass and that r_{13} itself is an estimate of 1.

While this position is perhaps logically tenable it seems a little impractical. For a single constituent we usually regard the sample mean and standard deviation as estimates of population parameters themselves subject to variation. We do not suppose, for instance, that the Barre granite everywhere carries exactly the same amount of plagioclase and muscovite. In the same way we should be willing to grant that b_{13} is an

estimate of a ratio which varies somewhat ***in the parent*** quite independently of how we go about taking or measuring the sample. It follows that r_{13} will in general be less than 1 even in the absence of systematic effects tending to destroy the correlation. Residual variance on this construction must include not only experimental error and the influence of non-magmatic factors, but also random and possibly systematic variations in the parent value of b_{13} such as are not opposed to the hypothesis that $\rho > 0$.

Proper analysis of the residual variance is thus a complex matter concerning which a sample as small as that shown in table 1 provides very little relevant information. Variations in the regression coefficient from place to place in the mass—whether random or not—would materially reduce the value of r_{13} found in a sample taken without regard to them. Such variations would almost inevitably result from variations in the duration of the late-magmatic stage from place to place. And it is certainly an over-simplification to suppose that the time during which the conversion of O to R might occur was everywhere exactly the same, even in the absence of a physical separation of crystallized material and magmatic residues. My own hunch is that much of the residual variance is introduced by local variations of this type, and hence not necessarily opposed to the hypothesis that the muscovite of the Barre granite is of late-magmatic vintage. This is pure speculation however; the problem could be solved by means of a considerably larger sample taken so that reasonably reliable estimates of r and b could be reached for different parts of the mass. A further study of this sort would surely be worthwhile.

CONCLUSIONS

The distribution of the products of pseudomorphous replacements in a rock mass will depend on the distribution of magmatic residues through the mass at the time of the reaction. If the reaction occurs before these residues have been expelled from some parts of the chamber and concentrated in others, the amount of replacement mineral (O) formed will be roughly proportional to the amount of original mineral available for the reaction (R). There will be positive correlation between O and R and it is not likely that correlation between O and (O-R), the amount of original mineral surviv-

ing the reaction, will be significantly negative. Proportionality between O and R, as expressed in the regression coefficient of R on O, will no doubt vary from place to place even under these conditions, but it should always be positive. In a sample taken without regard to such variations the proper test is thus not whether the parent correlation might be perfect but whether it might be larger than zero.

If the reaction does not occur until there has been extensive separation of liquid residue from crystallized material, however, the amount of R will be essentially independent of O, and the quantities R and (O-R) will be negatively correlated.

It is proposed here that if the products of pseudomorphous replacements are distributed through the rock according to the first case they be termed late-magmatic, that if they come under the second they be called post-magmatic, and that the term hydrothermal be reserved for cases in which some at least of the reagents have reached their present sites *via* fractures in the rock.

On this basis it is shown that the relation between plagioclase and muscovite pseudomorphously replacing it in the Barre granite is conformable with the first, or late-magmatic, reaction type. The correlation is high enough to be significant in a probability sense but low enough to leave much of the variation unexplained. From a sample large enough to permit estimates of regression and correlation coefficients for different portions of the Barre mass it would be possible to determine how much of this residual variance is to be attributed to post-magmatic and hydrothermal effects and how much to variations not opposed to the hypothesis that the reaction is late-magmatic.

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AN EXPOSURE OF THE TRIASSIC EASTERN BORDER FAULT IN CONNECTICUT*

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ABSTRACT. A recent excavation along State Highway 77 one-half mile north of Lake Quonnipaug, New Haven County, Connecticut, has resulted in the first extensive exposure of the eastern border fault of the Connecticut Valley Triassic basin. The exposure marks part of the northern termination of the Totoket crescent, the curved edge of a local synclinal basin of the Late Triassic Middle or Main lava flow. The Triassic rock is highly brecciated within 25 feet of the fault at this exposure, as is the pre-Triassic Bolton schist east of the fault. Separating the two, and exposed for a length of nearly 300 feet, is a band of fault gouge 3 feet wide and consisting of dark microbreccia with numerous light colored gouge streaks. At this exposure the fault has a strike of N. 5° E. and dips 55° W., which verifies previous claims for the border fault as a high-angle normal fault. This exposure shows that the Triassic lava flows reached the fault, at least locally, in Newark time rather than wedge out everywhere against detritus at the base of the scarp.

INTRODUCTION

THE purpose of this paper is to call attention to a recent exposure of the eastern border fault of the Connecticut Valley Triassic basin. This is the only existing exposure of the contact of the Triassic rocks with the pre-Triassic crystalline rocks of the Eastern Highland of Connecticut. The location is easily accessible and the exposure is large, but projected highway construction will cover much of the exposed rock within a few years. The Triassic rock at this contact is the trap rock of the Middle or Main flow sheet rather than the detrital rocks common to the eastern margin of the Newark group of this basin; and for this reason the exposure has additional significance.

Highway construction during early summer of 1948 along State Highway 77 in the area of Lake Quonnipaug, Connecticut, included excavation of two sight line cuts[1] on this highway. One of these cuts, near the south end of Lake Quonnipaug, enlarged an exposure of the coarse conglomerate of the eastern border of this Triassic area for which the Lake Quon-

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[1] A slight line cut is made at a highway curve to provide view beyond the curve.

nipaug region is well known geologically. The other cut, half a mile north of Lake Quonnipaug, exposed the fault contact discussed in this paper. The writer first observed these cuts during final stages of their excavation while he was employed by the Connecticut Geological Survey in mapping this region.

LOCATION OF EXPOSURE

The sight line cut resulting in the fault exposure is an excavation on the west side of State Highway 77 midway between Quonnipaug Mountain and Bluff Head and approximately 4.2 miles south of the intersection of this highway with State Highway 17 at Durham Center, Connecticut. The cut was made on the property of Amelia Rusconi, in the town of Guilford. Location of the cut by Army grid system is 102774 x 210970, Army Map Service Durham quadrangle, Connecticut.

DESCRIPTION OF FAULT EXPOSURE

Exposure at this locality produced a nearly horizontal platform with a maximum width of 60 feet between the highway and the base of the nearly vertical, freshly cut cliff. The cliff is approximately 400 feet long at its base and approximately 40 feet high. The floor of the platform consists of brecciated schist. Some of this rock has been disturbed by blasting and by the construction machinery. The rock of the cliff face is a highly brecciated dolerite or basalt. At the base of the cliff, and separating the cliff rock from the schist, is a band of fault gouge.

Megascopic investigation of the schist in the platform area revealed an increasing intensity of brecciation progressively westward from the highway to the gouge band. Within 10 feet of this gouge band the individual fragments of schist breccia cannot be resolved with the unaided eye. Two additional outcrops of the schist may be seen on the east side of the road, opposite the fault exposure. These outcrops appear to be the normal muscovite-biotite schist commonly found east of the fault in this area. These two exposures are about 120 feet from the fault and are not markedly brecciated. Thus the width of intensely brecciated schist, as indicated at this locality, is somewhat less than 120 feet. Several large fragments of unbrecciated pegmatite, however, may be found with the brecciated schist in the platform. Some of this pegmatite is within

several yards of the gouge and appears to be in place. Several specimens of schist breccia with highly polished slickensided surfaces were found near the gouge but were apparently not in place. Two thin-sections of the schist breccia were prepared from specimens collected 4 feet and 40 feet respectively from the gouge zone. Study of these revealed that the composition and texture of the breccia fragments are typically those of the schist formation of this general area, although much of the biotite shows alteration to chlorite. More intense brecciation was noted in the section prepared from rock closer to the gouge zone.

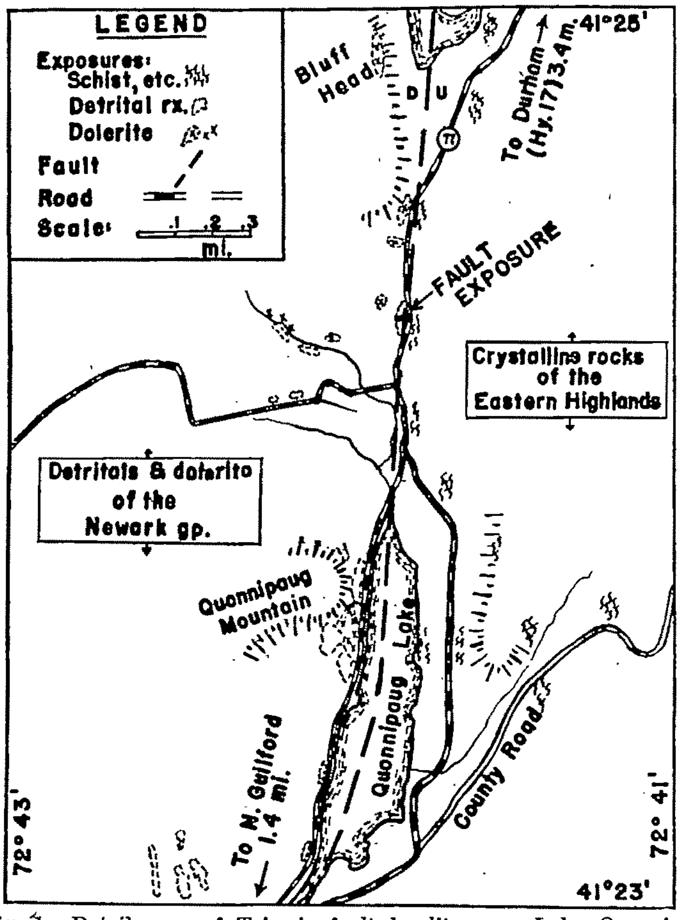

Fig. 1. Detail map of Triassic fault locality near Lake Quonnipaug, Connecticut.

The rock of the cliff face is more difficult to interpret megascopically. A fresh surface shows a gray, mottled compact breccia with fragments barely resolvable with the unaided eye. The rock is filled with a network of thin calcite veinlets, most of them less than one-half inch in width. Some vugs with calcite crystals up to one inch long may be seen. In appearance this rock differs markedly from the typical trap rock of the Connecticut Triassic. The high specific gravity of the cliff rock and the presence of several near-by exposures of normal trap rock (see fig. 1), however, do suggest the two are the same. Under the microscope the rock of the cliff face shows fragments most of which clearly possess ophitic fabric. Some of the plagioclase laths show alteration to clay minerals and some sericite has developed in the rock.

The base of the cliff strikes N. 5°-10° E., and it is here that the band of fault gouge is displayed (see fig. 2). The band is 3-4 feet wide and is quite clearly definable from the adjacent material. When freshly exposed the gouge was very plastic, and with little effort the writer was able to push a shovel handle into the material to a depth of three feet. The strike of the fault gouge band is uniform and was measured as N. 5° E. Its dip is measurable at several places where the gouge was not removed from the cliff face. Ten dip readings between 50° W. and 60° W. were recorded; one was 35° W.

The excavation procedure was discussed with the construction foreman, and it was stated that three horizontal cuts were made to reduce the area to the present level. He described the position at which the "clay belt" was discovered at each level, and from this discussion it was revealed that the band of gouge maintained a dip of about 55° W. through the material removed.

The gouge is a dark gray to black microbreccia with most of the fragments less than one millimeter in size. Streaks of cream-colored to white gouge are present within the darker gouge. These light streaks, seldom over one centimeter wide, parallel the length of the gouge zone and are several inches to several feet in length. The dip of the light streaks at several places was found to be about 55° W.

SIGNIFICANCE OF EXPOSURE

For most of its length in Connecticut and Massachusetts the eastern contact area of the Triassic basin is cloaked by

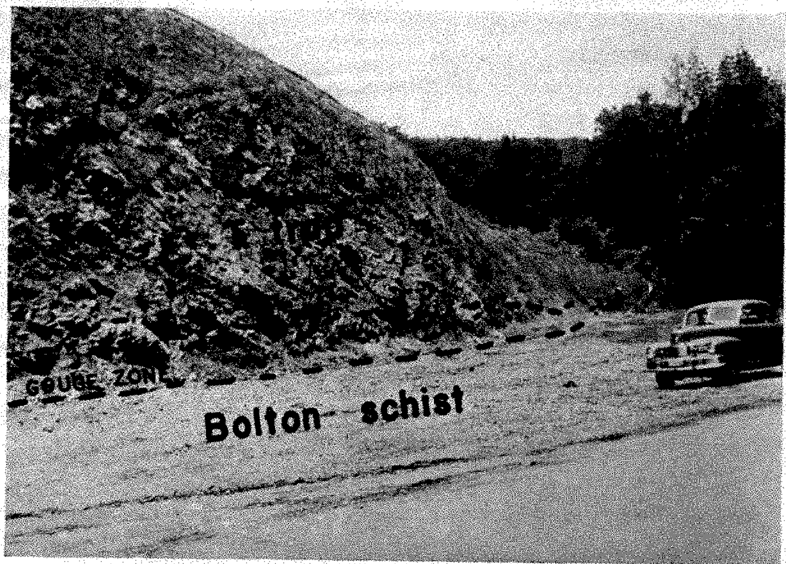

Fig. 2. Photograph of the Triassic border fault exposure near Lake Quonnipaug, Connecticut. The band of fault gouge is visible at the base of the cliff between the brecciated trap rock of the cliff and the brecciated schist of the platform. View looking northwest.

glacial debris. Stream valleys occupy much of this contact area. Rarely do the Triassic and pre-Triassic rocks occur closer than 20 feet to each other. At one place, three-tenths of a mile north of the locality here described, Triassic dolerite and pre-Triassic schist of the Bolton formation occur on opposite sides of the road (see fig. 1), but the actual contact is not observable.

Bain (1932)[2] noted that "the only known exposures of the eastern contact (of the Connecticut Valley Triassic) are near and on either side of Roaring Brook, Massachusetts." In his paper the contact is described and pictured as an overlap of Triassic talus on a steeply inclined pre-Triassic surface. It is generally agreed, however, that this contact is a fault contact in Connecticut and much of Massachusetts. This fault has been commonly referred to as the Great Fault. Davis, in his classic monograph on the Triassic formations of Connecticut (1898) and in earlier papers, described the fault as a high-angle normal fault. All subsequent writers on the Connecticut Triassic agree with this and with Barrell's contention that an important part of the faulting was contemporaneous with most of the Triassic deposition (Barrell, 1915, p. 29). Unable to locate a natural exposure of this contact, Davis (1898, p. 131) revealed it by means of a test pit at Highland Park, Manchester Town, Connecticut. He found "the actual contact fault plane—(with) a dip of 55° to the west, with strike north and south."

W. L. Russell (1922, p. 490) has described a quartz lode that occurs along the eastern side of the fault area in southern Connecticut. Fragments of this quartz material are found in the adjacent Triassic sediments. He believed that this quartz lode was introduced along a pre-Newark fault and that this fault determined the location of the Great Fault. From the attitude of this quartz lode, and from other evidence, Russell gave a westward dip of 30° to 60° for the Triassic eastern border fault.

Keeler and Brainard (1940) have described fault contacts between the Newark Mount Toby conglomerate and a pre-Triassic phyllite near the French King bridge east of Greenfield, Massachusetts. The fault, which dips 60° west at one locality and 35° west at a second locality, is considered to

[2] References cited are listed at the end of the paper.

be part of the eastern border fault of the Connecticut River Triassic basin, but it is stated that the faulting may have occurred entirely at the end of the Triassic rather than partially contemporaneous with Newark sedimentation.

A persistant ridge maker in the Triassic Lowland area of Connecticut is the 400-500 feet thick Main or Middle trap sheet of the Meriden formation (stratigraphic divisions by Krynine, 1941). The Lower or Anterior and Upper or Posterior trap sheets separate this formation from the Lower Newark New Haven formation and Upper Newark Portland formation of the Connecticut Triassic. These lower and upper sheets are thinner than the middle sheet and in places do not have topographic expression. The three dolerite flows have been the principal stratigraphic guides in this province. Gentle warping in the vicinity of the Great Fault produced several crescent-shaped ridges of the Main trap sheet and the Upper trap sheet. These curved ridges are especially well developed in southern Connecticut (see fig. 3). They indicate synclinal areas and are concave toward the Great Fault. Wheeler (1939) has expressed the belief that the warping was related to differential movement along the Great Fault. The crescents of the Main trap sheet are called (south to north) Saltonstall (Pond), Totoket, and Deerfield. Smaller crescents produced along the outcrop trace of the Upper flow exist within the larger crescents of Saltonstall and Totoket.

At the time these great lava sheets were extruded it is conceivable that they (1) may have wedged out to the east against alluvial and talus material of the fault area, (2) may have abutted against a fault scarp, or (3) may have flowed beyond the deposition area onto the eastern crystalline rocks for an unknown distance. It is possible, too, that each of the abovementioned conditions may have been manifest at different places along the length of the Great Fault, depending locally upon such factors as position and thickness of alluvial and talus material, slope of the surface, thickness of the lava, and height of the fault scarp. At the various places where the trap ridges lie near the border fault coarse conglomerate is found. The conglomerate at many of these places consists of fragments that range in size from silt to blocks 3-4 feet in diameter. Many of the fragments are extremely angular, indicating short distance of travel; yet a semblance of bedding can be seen,

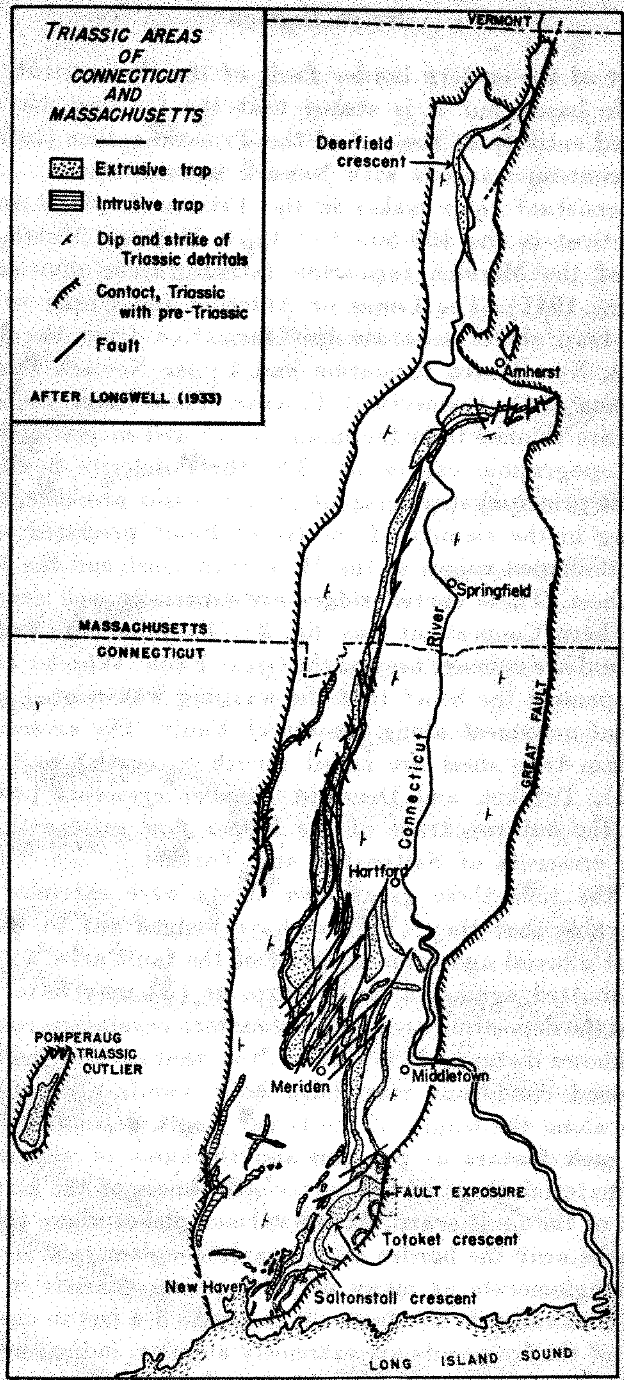

Fig. 3. The Connecticut Valley Triassic belt, showing location of the Lake Quonnipaug fault exposure area and showing the crescent-shaped pattern of the trap flows near the eastern margin of the belt.

and this, together with the localized distribution of the coarse debris, suggested to Longwell (1922, p. 232) that the material may be a fanglomerate. The fault scarp was probably not over a few hundred feet high at the time of formation of this fanglomerate, for large fragments are only locally abundant and even in these places seldom exceed two feet. A high fault scarp would have produced larger fragments. The relation of the conglomerates to the trap near the fault indicates that faulting was active at the time of or just before the lava outpourings.

The possible juxtaposition of the trap rock of the flows with the pre-Triassic crystalline rocks at the fault line has not been considered in most of the literature of this area. Longwell (1922, p. 234) states that the Upper flow at one locality within the Saltonstall crescent wedges out in fan material west of the Great Fault, and Bain (1932, p. 62) and Longwell (1933, p. 100) suggest that the Deerfield sheet of Massachusetts overlaps onto coarse deposits along the eastern border of the Triassic in this part of the Lowland.

The fault exposure described in this paper shows a contact of the northern part of the Totoket crescent with the crystalline rocks of the Eastern Highland of Connecticut. A review was made of eight maps of the Connecticut Triassic which include this location.[3] In only three of these maps (Gregory & Robinson, W. L. Russell, Longwell) is the trap rock of the Totoket crescent mapped in contact with the pre-Triassic rock at this place. There are 15 places where contact of trap and pre-Triassic crystalline rocks is theoretically possible along the eastern margin of the Connecticut Valley Triassic belt (see fig. 3). Such contact is generally not indicated for these places in the various maps of the Connecticut Valley Triassic.

In the early geologic mapping of the Connecticut Triassic considerable dependence was placed on topography. In most places the trap rock was mapped only where it has topographic expression as ridges. Davis emphasized that the lava sheets were cut by the numerous oblique faults existing throughout the area, yet his map gives the impression that at many places (as at Reed Gap) the flows pinch out short of these faults. Davis also considered that the eastern border

[3] Percival (1842), I. C. Russell (1892), Davis (1898), Gregory and Robinson (1906), W. L. Russell (1922), Longwell (1933), Wheeler (1939), and Krynine (1945).

fault was post-depositional and that the sediments and lava flows extended for a short distance east of this line prior to faulting and uplift of the eastern block (Davis, 1898, fig. 29). His map, however, does not show contact of trap with the eastern crystalline rocks. It is clear that Davis' map, which has been the guide for so many later maps, does not fully accord with his own views. In compiling the map conditions of topography were probably stressed above requirements of structure.

The fault contact exposure described in this paper is observable evidence of the existence and nature of the long postulated Triassic eastern border fault in Connecticut. The evidence from this exposure and from other outcrops near the fault in the Lake Quonnipaug region strongly indicates that the Triassic lava extrusives did flow against or beyond an eastern scarp at least locally.

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A NEW COTYLOSAUR FROM NORTH CENTRAL OKLAHOMA

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ABSTRACT. A Permian reptile skull new to science is described. Its appearance is so like *Labidosaurus* that it was at first thought to be that genus. Its excessive size and the batteries of teeth in the maxillaries and dentaries clearly indicate a new genus. It doubtless is a member of the family Captorhinidae. That it came from an area in which other very large Permian vertebrates have been found may indicate something of the ecological conditions in north central Oklahoma during Lower Permian time.

INTRODUCTION

Classification:

- Class Reptilia
  - Subclass Anapsida
    - Order Cotylosauria
      - Suborder Captorhinomorpha
        - Family Captorhinidae

Labidosaurikos meachami gen. et sp. nov.

Genotype: skull and right mandible, M. U. O. No. 3-1-S2.

Generic and specific characters: larger than *Labidosaurus*; one round, large premaxillary and anterior dentary tooth; a battery (six rows) of remarkably uniform maxillary and dentary teeth; small nares; tabular and dermosupraoccipital posterior to parietal, and extending on top of skull; ratio of orbit to skull length smaller than in *L. hamatus*.

DISCUSSION

A skull of a Permian cotylosaur, found near Crescent, Oklahoma, was presented to the writer in 1939. Illness has prevented its previous description. The specimen is an excellent one and shows most of the skull features quite distinctly. Several features, notably the occurrence of six rows of simple conical teeth on both the maxillary and dentary (plate 1, figs. d, f), its excessive size, and the arrangement of the tabular and dermosupraoccipital partially on top of the skull, indicate an animal new to science.

The skull was found in Hennessey shale in the bank of a small creek one half mile east and one and a quarter mile north of the north edge of the little town of Crescent, Logan County, Oklahoma. No more of the skeleton was found, but

associated with it were vertebrae and a portion of the pelvis of *Dimetredon*.

The specimen is almost complete, and all of its features are present and distinguishable on the right side (plate 1, figs. a, b). The large premaxillary tooth, however, was broken off and buried in the matrix. All of the right mandible is present except a small portion at the symphysis.

When first examined, the specimen was thought to be a species of *Labidosaurus*, probably *L. hamatus*. This was because the general contours of the Crescent skull closely resemble those of *Labidosaurus*. The teeth, as then visible, were similar in both animals. There appeared to be more than 16 maxillary teeth as recorded by Williston (1908, p. 145) in *L. incisivus*. The removal of a small amount of matrix from the inside of the jaw revealed upper and lower teeth in that position. This suggested a battery of teeth in the maxillary and dentary bones instead of a single row as in *Labidosaurus*. X-rays confirmed this supposition. The mandible was then removed and six rows of conical, peg-like teeth were revealed in the maxillary and five rows in the dentary. Fragments of teeth indicate that in life there were also six rows in the dentary. The short row contains seven teeth while the other rows have a maximum of 34. The smaller number is on the lingual side of the maxillary and on the cheek side of the dentary (plate 1, figs. d, f). There is also a tendency toward lineal arrangement in a transverse direction.

The crowns are conical but show a slight amount of wear on the lingual side of those in the maxillary and on the cheek side of those in the dentary. Neither the wear, the number, nor the arrangement of the teeth offers conclusive evidence as to diet. The feebleness of the teeth suggests soft food, and the presence of four large teeth in the anterior portion of the mouth suggests a diet of soft plants.

In the posterior half of the maxillary, the teeth are remarkably uniform in height and size. Anterior to these, several smaller teeth are worn flat. Between these and the large premaxillary tooth, there are two or three peg-like teeth that are larger than those in the posterior half of the maxillary. They, like the single, large, recurved premaxillary tooth, are flanked by small, sharp pointed peg-like teeth.

The teeth are replaced by growth from a pulp cavity. Some

of the teeth have been exposed to considerable depth by the removal of an outer layer of bone along the margin of the maxilla and dentary, thus giving the appearance of normal sockets; although it is impossible to say whether they are true thecodont or set in grooves as in young alligators. Longitudinal openings filled with matrix along one or both sides of the teeth may be either fractures or natural grooves. One thing is certain, the teeth are surrounded by bone; and the large anterior maxillary and dentary teeth are set in true sockets.

There is a single, strong, recurved tooth in each side of the premaxillaries and in each of the dentaries. Neither of the premaxillary teeth are present in place, although one was broken off and preserved in the matrix. It is round and not chisel-like. The large tooth was present and complete in the anterior end of the mandible. These teeth are suggestive of corresponding teeth in *Limnoscelis* (Romer, 1946, fig. 3, p. 154), but are less recurved and relatively shorter. Also in *Lim-*

EXPLANATION OF PLATE 1

Labidosaurikos meachami gen. et sp. nov.

Maximum length of skull ....295 mm.
Maximum length of mandible ....267 mm.

Figure *a* — Dorsal view.

Figure *b* — Lateral view taken before the mandible was removed from the cranium.

Figure *c* — Lateral view after removal of the mandible.

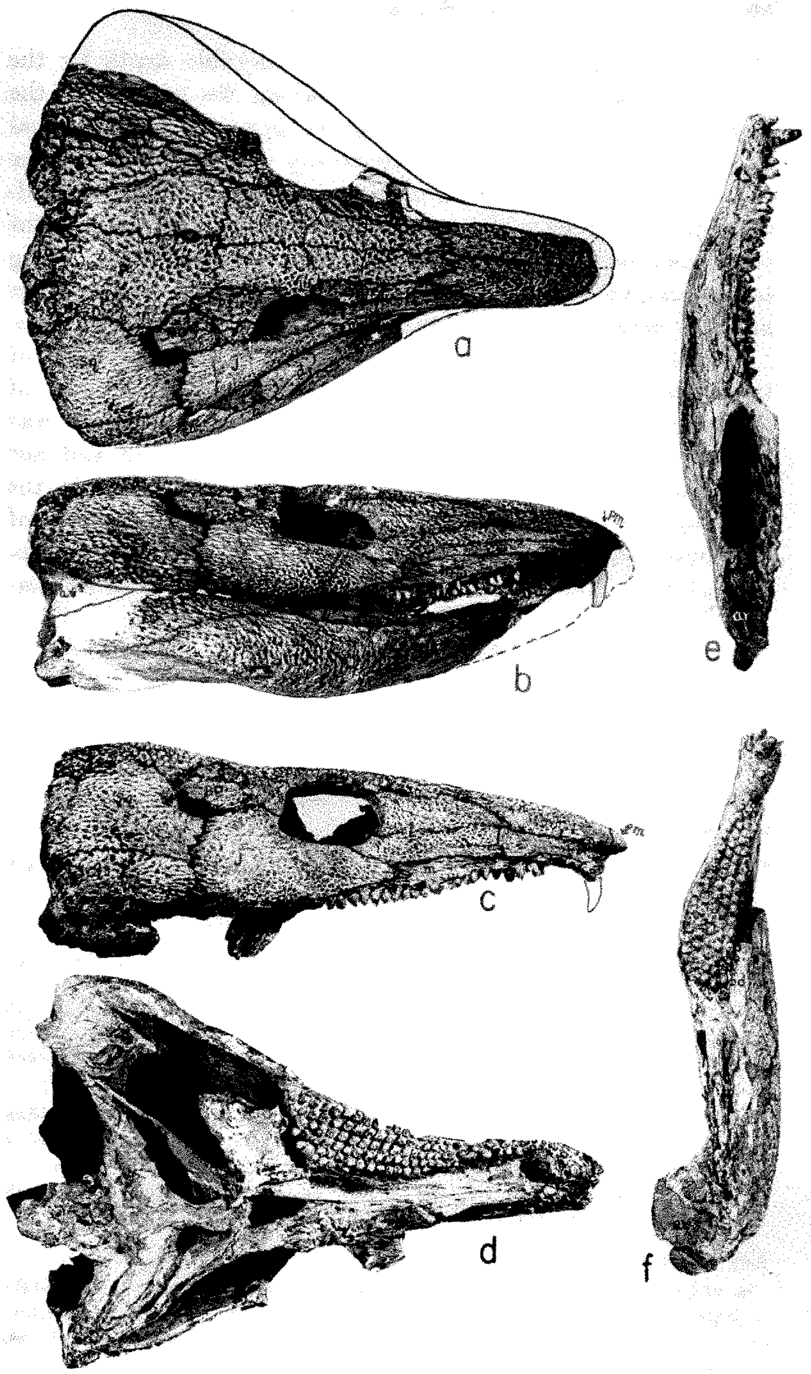
Figure *d* — Ventral view showing tooth arrangement. The scar of the large premaxillary tooth, the small teeth immediately behind it and the palatine teeth have been retouched in the photograph in order to show their true character. The dark area toward the anterior end represents the place where the large dentary tooth penetrated the palate.

Figure *e* — Lateral view of right mandible showing the large Meckelian fossa. The small elongate dark spot near the bottom and a little in front of the middle is the infra-Meckelian fossa.

Figure *f* — Dorsal view of the right mandible showing the tooth arrangement.

Key to the bones in Plate 1:

a, angular; ar, articular; d, dentary; do, dermosupraoccipital; f, frontal; j, jugal; l, lacrimal; m, maxillary; n, nasal; p, parietal; pf, postfrontal; pm, premaxillary; po, postorbital; prf, prefrontal; qj, quadratojugal; sa, surangular; sq, squamosal; t, tabulare.


a
b
c
d
e
f

noscelis there are three large teeth in each premaxillary and dentary and no tiny teeth around the base of the large teeth.

There are many tiny tooth tubercles on the pterygoid and palatine bones. They are arranged in a row along the margin of the palatine vacuity and in an irregular mass along the summit of each transverse bone. A small cluster present in the lateral depressions of the palatines of the Williston specimen of *Labidosaurus* appear to be present in a single line in the Crescent specimen.

There is no visible distortion in the specimen except at the anterior end of the dentary; the sculpturing is pronounced although definitely not in rows, and the sutures are, in general, easily distinguishable. On the basis of arrangement and shape of the skull bones, this animal appears most closely related to *Labidosaurus*, although it appears to be much more advanced than that genus. Little can be told concerning the premaxillaries because only a small portion of those immediately anterior to the nasals has been preserved.

Comparison with *Labidosaurus hamatus*, which this animal closely resembles, will be of value. The orbits and nares are elliptical, with the longer diameter extending antero-posteriorly. In the type of *L. hamatus*, the long axis of the orbit "enters the length of the cranium posterior to it twice, and one and three quarters times the length anterior to it . . ." (Case, 1911, p. 46). In the Crescent specimen, these measurements are 2.5 and 3 plus times respectively. Thus the orbits in the Crescent specimen are relatively much smaller and not so centrally placed. There is considerable difference, too, between the ratios of maximum orbit diameter to total maximum skull length. In the Crescent specimen, this figure is six, while in the Williston specimen it is about 4 5/6. The pineal opening is six by nine millimeters. Between the orbits and slightly behind them, the cranium is a curved plane which, in a lateral aspect, appears slightly depressed. The posterior portion of the skull forms an arc of a circle; the mandible is not visible from above in *Limnoscelis* while in this specimen it is readily seen from above, apparently not as a result of distortion.

The most noticeable superficial difference between this specimen and the one described by Case (1911, pp. 47, 111) is its size, as may be seen in the following table of measurements.

Comparative Measurements in Millimeters

	Labidosaurus hamatus Cope — Williston	Labidosaurus hamatus Cope — Univ. of Chicago* #641	Labidosaurus hamatus Cope — Broili	Labidosaurikos meachami n. sp. This Specimen
Maximum length of cranium ..	162	155 (est.)	185	295
Maximum width of cranium ..	147+			240
Interorbital width	32	26	27	49
Diameter of orbit:				
Anteroposterior	36	23**	4	54
Vertical	22	12**	3	40
Width of muzzle at posterior border of nares	29	30 (approx.)		48
Depth of muzzle at posterior border of nares	21	13**		30
Depth of cranium at middle of the orbit	35	26**		72
Length of crown of large premaxillary tooth		9**		16±
Maximum diameter of large premaxillary tooth		3**		8
Depth of mandible at middle of orbit	20	18**		42
Length of mandible	170	150		273+
Length of crown of large dentary tooth				15
Diameter at base of large dentary tooth				10

* These measurements are considerably greater than those indicated by the figures in plate 12 of the Case report.
** Taken from figure.

The frontal bones are a little more than one third the total length of the skull, have parallel sides and terminate posteriorly in a line perpendicular to the antero-posterior axis of the skull. This suture in the Cope specimen forms a "V" with its point directed anteriorly. The postfrontals and postorbitals are short and differ slightly in size, while the prefrontals are long and slender, and the lacrimals are wide at

the orbit and extend forward in a narrow wedge to the nares. The postfrontals articulate with the frontals above, the parietals behind, and the postorbitals and orbit below. The postorbitals are bordered behind by the parietals and squamosals, and by the squamosals and jugals below (plate 1, fig. a).

The external nares are not well shown in the Crescent specimen, but the posterior margin of the right naris is present. A small narial opening is indicated. Its greatest diameter lacks four and one half, and possibly as many as five times, of being as large as the greatest diameter of the orbit; thus differing from the Williston specimen, in which a little more than two and one half diameters equal the diameter of the orbit.

The nasals form the superfacial region for only a little more than half the distance between the tip of the rostrum and the orbits. In *Labidosaurus*, the posterior margin of these bones is only a short distance in front of the orbits and is in contact posteriorly with the frontal, prefrontal, and lacrimal.

Williston says: "On the posterior or occipital side there are two cranial roof bones on each side, clearly and positively shown in all specimens, one bordering the hind margin of the parietal, and the other the squamosal, called by Cope respectively the supraoccipital and the tabulare—that is, the so-called epiotic of authors. They differ from the bones of the upper surface of the skull in lacking the superficial markings or pittings, and are suturally united with the superior bones at an angle of nearly ninety degrees" (Williston, 1910, p. 75).

This condition differs from that of the Crescent specimen in several important ways. The parietals do not extend to the posterior margin of the skull. Those bones are in contact with the dermosupraoccipital and tabulare on top of the skull at a distance of about 18 millimeters in front of the angle. The median pair, that is the dermosupraoccipitals (the postparietals of authors), apparently form the posterior roof of the brain case, the suture with the opisthotic being quite close to the *foramen magnum*. The tabulares extend downward about 12.5 centimeters at an angle of 90 degrees in a sort of apron. No suture is visible at the angle, and hence the paroccipital is not present as a separate bone. The squamosal joins the parietal and tabulare mesially and extends downward at the posterior angle in the same way and to

about the same extent as the tabulare. The quadratojugal is thus not present behind and below the squamosal as a single bone as shown by Williston (1910, plate 2, fig. 2). The quadratojugal is lateral to the squamosal and turns down the posterior margin very much in the same manner as the squamosals.

The jugals begin well in front of the orbit and not in front of their middle as described by Williston (1910, p. 77). They articulate behind with the squamosal and quadratojugal in a distinct suture instead of extending "nearly to the hind margin of the skull." No quadratojugal was recognized in *Labidosaurus* by Williston and Case. Williston said, "If there is a distinct bone here on the lateral margin of the squamosal), I suppose that it must be the real quadratojugal, notwithstanding it has no articulation with the quadrate" (Williston, 1910, p. 74). In the present specimen the suture between the quadratojugal and jugal is unmistakable.

The description of *Labidosaurus* given by Case (1911, p. 45) does not agree with this specimen in several points. The maxillae of this specimen terminate laterally a little in front of the posterior margin of the orbits. The nasals terminate about midway between the orbits and nares and not "a little in advance of the orbits." The prefrontals are similar in the two specimens but here terminate anteriorly at about the same place as the frontals and not in front of the frontals as in the Williston specimen. The lacrimals and frontals are essentially as in the Case specimen. The relative size and relationship of the postfrontals and postorbitals are similar in the two specimens. The jugals are quite different in the Crescent form, terminating in front at the anterior margin of the orbits. The posterior margin of these bones is broadly in contact with the squamosals and quadratojugal at about one third of the distance between the orbit and posterior margin of the skull. Case (1911, p. 103) considered the possibility of sutures in this position on specimens 4427 and 4876 of the American Museum of Natural History and numbers 641 and 642 of the University of Chicago, but concluded that the supposed sutures were fractures in the same place on each side. In the Crescent specimen, however, the sutures in this position are distinct and show feathering off of the squamosal and quadratojugal on top of the jugal.

The parietals are large, rectangular bones that terminate posteriorly on top of the skull and not at the angle as in *Labidosaurus* and *Dimetredon*. Immediately posterior to these bones are the well-sculptured tabulars and supraoccipitals. These two bones were recognized in *Labidosaurus* by Williston (1910, p. 75), but they did not extend upward beyond the angle of the skull. Furthermore, in the Williston specimen the entire parietal was bounded behind by the supraoccipital and the squamosal by the tabulare.

The Crescent specimen differs from *Limnoscelis* in many essential features, but is only slightly larger. The orbits of the latter are more elongate, and there are six large, elongate, recurved rake-like teeth in the anterior part of the mouth, while there are only two in this specimen. In *Limnoscelis*, the stapes and postorbital slightly overhang the squamosal, while in *L. meachami* the posterior part of the skull forms an arc of a circle.

Most of the comparisons above have been made with *Labidosaurus*, although there are many features of the Crescent specimen that are suggestive of *Captorhinus*. The general contours of the skulls of the two animals are similar. Both have hook-like anterior teeth. Both have batteries of short, peg-like teeth in the upper and lower jaws. Both have tiny teeth in about the same position in the roof of the mouth. But the great difference in the size of the two animals precludes generic relationship.

The generic name *Labidosaurikos* was given to the Crescent specimen because its general appearance is so much like that of *Labidosaurus*. The specific name, *meachami*, is in honor of Dean E. D. Meacham who has been consistently helpful to faculty and graduate students engaged in research at the University of Oklahoma.

During the past few years, three exceptionally large Permian vertebrates have been discovered in north central Oklahoma. The present specimen, *L. meachami*, is the largest captorhinid known to the writer. In a previous paper, the writer reported what appears to be the largest known American Permian reptile, and in January of 1948 he reported an unusually large embolomerous amphibian (Stovall, 1937, 1948).

All of these specimens came from the same general area and within a few hundred feet of each other vertically. It has not

been determined whether there is any significance in this fact. Some possibilities suggest themselves. Can these excessive sizes be accounted for by special conditions that influenced the evolution of these animals, or may their large size be accounted for by the lingering on of favorable Permian habitats in this area? *Cotylorhynchus romeri*, the large reptile referred to above, appears to be the most recent of the Permian vertebrates. Since the area has not been completely worked, additional exploration should prove profitable, especially if stratigraphic or paleontologic evidence can be found to correlate this area with the north Texas and southern Oklahoma region.

ACKNOWLEDGEMENTS

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CLASSIFICATION OF SEDIMENTS

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ABSTRACT. In this article the grade scale tentatively in use by the Maine Geological Survey is presented and two new sediment classification triangles are proposed. One of the triangles is for unconsolidated mixtures of sand, silt, and clay grades. The other is for consolidated sediments. No new terms are introduced but quantitative definitions of group limits are set by the fields of the triangles.

MANY workers are concerned with sediments; the largest groups directly concerned are civil engineers, agronomists, and geologists. To the civil engineer soil classification is not an especially pressing problem, for with the development of soil mechanics, it is now widely realized that the soil of each particular project may differ significantly in its properties from any other soil similarly classified from any other location; and that even within similarly classified soil groups of one narrowly restricted area, significant differences often appear. Nevertheless, classification of general soil types is often an engineering convenience, and engineers have proposed a number of classifications (Casagrande, 1947). A few of these have been widely used. The agronomist, likewise, feels the need of systematic groupings, and has contributed a variety of classifications. Geologists, also, have presented classifications of the regolith and its consolidated counterparts. Each of these three principal groups has different needs which are reflected in some of the classifications of each group. An engineering classification, based on responses to loading and stress, an agronomic classification based on soil profile development, and a geologic classification based on agent of deposition are examples of three points of departure in classification.

It is obvious that no single classification will embrace the needs of the several groups. Indeed, a single classification will not satisfy the requirements of all workers within any one group, or even of an individual, for different aspects are brought out by different classifications.

UNCONSOLIDATED ROCKS

One base for classification, common to all who deal with the regolith materials, is found in the size grades and their proportions which compose a consolidated or unconsolidated

aggregate. A classification based solely on mechanical makeup is unsatisfactory because it does not take into account genesis of the deposits, and because the physical properties of aggregates with similar mechanical analysis may differ widely. Hence superimposed on a grain size scale are various qualifying schemes adapted to specific ends.

Four principal categories of particle size are commonly recognized: gravel, sand, silt, and clay. The numerical limits of these groups have been variously chosen, as shown by figure 1 (cf. Leggett and Peckover, 1949, p. 135). The International Scale (Atterberg) has perhaps had wider adoption than any of the others, although the Wentworth Scale has been used by many geologists. The grade scales shown on figure 1, except that of the Maine Geological Survey, divide gravel from sand at 2 mm., which is the ten mesh screen opening. To many geologists, however, sand includes material coarser

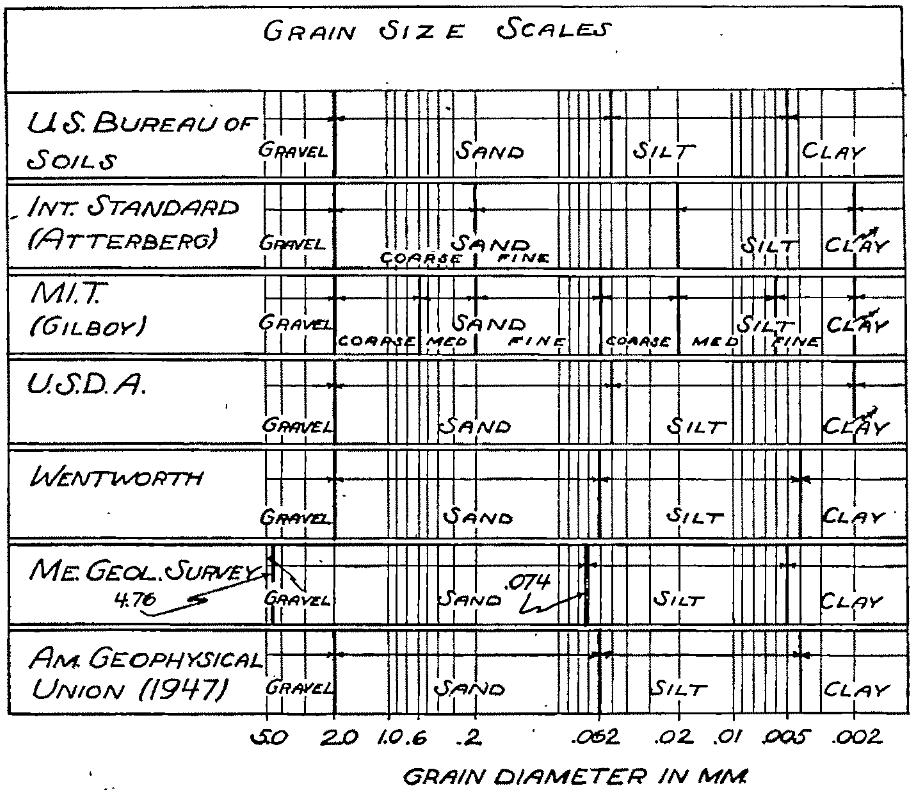

Figure 1. Comparison of Grade Scales.

than ten mesh. Indeed, Wentworth recognized an intermediate size, granules, between gravel and sand. The American Society of Testing Materials, however, limits gravel at four mesh (4.76 mm. opening), and this limit used in the various state highway testing laboratories has been adopted by the Maine Geological Survey. Most laboratory workers have found the two hundred mesh screen (.074 mm. opening) about the practical limit of sieving because of the difficulty of cleaning fine mesh screens, and of maintaining uniform mesh openings in finer screens. The Maine Geological Survey, therefore has selected .074 as the division point between silt and sand.

As seen from figure 1, the line between clay and silt has been chosen at various sizes. Some geologists (cf. Shrock, 1948, pp. 123-124) even have advocated dropping the term *clay* as a particle size term. Because most unconsolidated aggregates of clay size particles, however, do have general group characteristics not shared with silts, probably many will not wish to abandon the term as currently used. However, the suggestion has much to commend it, and as applied to the naming of consolidated equivalents may well be followed.

Field experience shows that most geologists call material *clay* that is coarser than laboratory limits set by some of the grade scales. A convenient reference point is .005 mm., which is the one used in the Maine Geological Laboratory.

After the mechanical analysis has been made by screening and some supplementary technique to extend the sizing of particles beyond the practical limits of sieving (200 mesh), the data are conveniently plotted as bar graphs (histograms) or cumulative curves. Mechanical analysis is routine laboratory procedure. It serves the purpose of discovering the mechanical composition of the sample, and supplies data from which a variety of inferences may be drawn.

With the data of mechanical analysis assembled and the class limits for clay, silt, and coarser particles chosen, many plot the analysis on a classification chart. A convenient type of classification chart for geologic purposes is the familiar triangular diagram. Civil engineers and agronomists, as well as geologists have use for this type of classification diagram. The one most widely used is that of the United States Bureau of Soils (fig. 2). This classification is quite satisfactory, but has the disadvantage of introducing *loam* into the series. *Loam*

is defined by Webster as "a soil consisting of a friable mixture of varying proportions of clay, sand, and organic matter." In this sense loam is widely known and sold all over the United States. Because of this general usage, engineers, agronomists, and geologists commonly consider the term unfortunately chosen to designate a mixture of definite proportions of clay, silt and sand which does not necessarily contain organic matter. There is, of course, no group of "loamstones" recognized by geologists. Further, the scheme is not easily retained in mind.

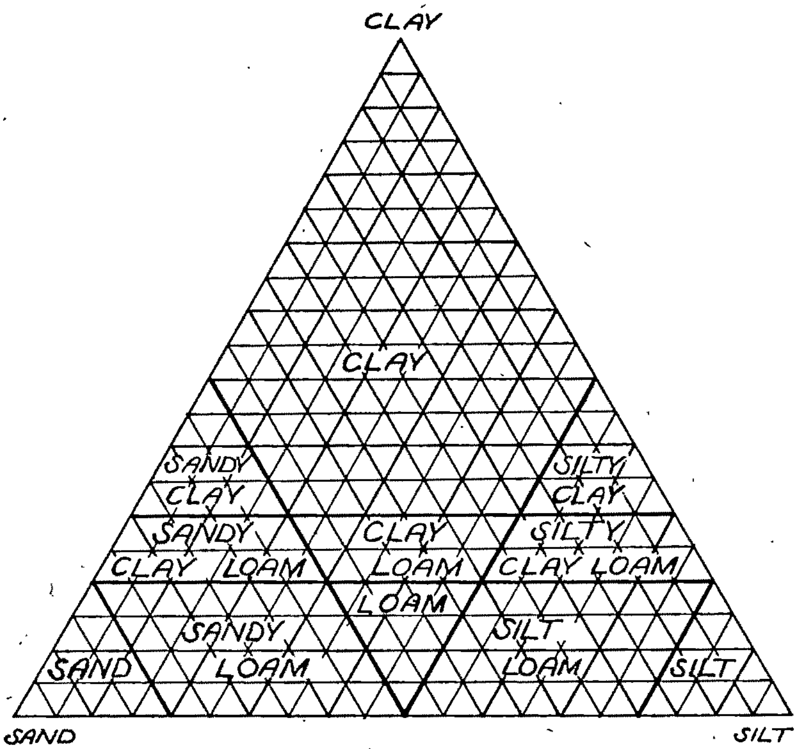

Figure 2. Soils Classification Triangle (U. S. Bureau of Soils).

A more recent triangular classification (fig. 3) devised by the U.S. Engineers of the Lower Mississippi Valley Division is better adapted to geological use. In this, loam does not appear. The divisions are not symmetrical, however, and some appear somewhat anomalous for a classification based on sand, silt, and clay proportions; thus by this diagram a material

classed as a "clay silt" might have more sand than silt, and a "clay sand" might have more silt than sand.

In the course of research on sediments along the Maine coast, the new classification presented as figure 4 was devised by the writer. In this the triangle is divided into thirds, that is into clay, silt, and sand fields. These major divisions are symmetrically subdivided to accommodate mixed groups. The simplicity and symmetry of the subdivisions and of the nomenclature are advantages of this system. This classification tri-

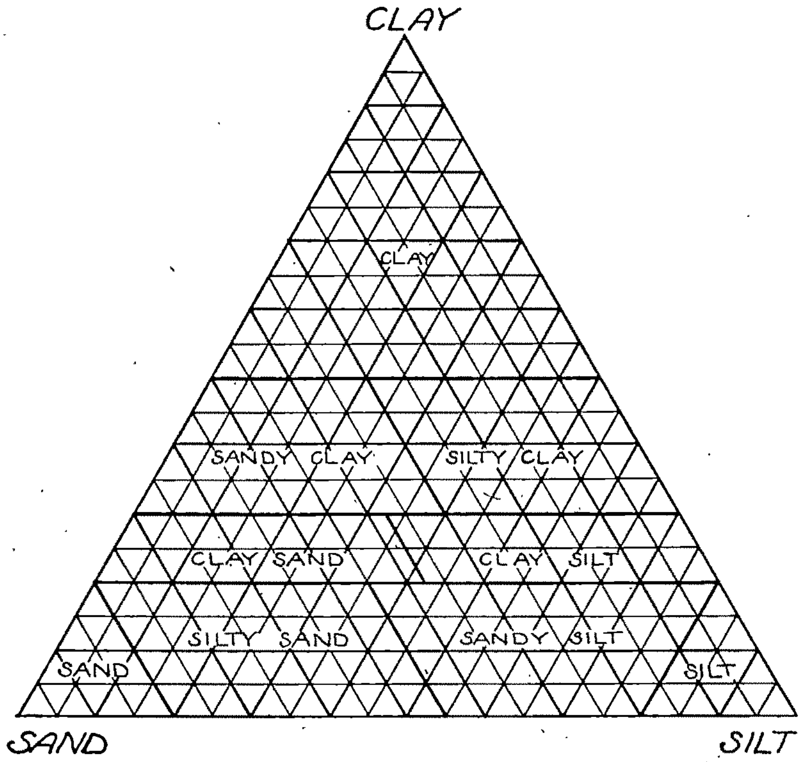

Figure 3. Soil Classification Triangle, U. S. Engineers, Lower Mississippi Valley Division (From Casagrande, 1947).

angle is based on mechanical analysis of sediments. It does not attempt to incorporate such properties as plasticity, water content, or other engineering properties that are dependent only in part upon mechanical make up, which are often variable, and which in large measure depend upon the field state of undisturbed material.

For the classification of aggregates consisting in part of material retained on the four-mesh screen, it is necessary to modify somewhat the diagram of figure 4. By placing silt and/or clay at one apex of the triangle, with sand and pebbles and coarser material at the other apices, the same divisions with appropriate modifications of nomenclature can be conveniently used. Thus a material may be called a boulder clay, cobbly or pebbly sand, or sandy silty gravel.

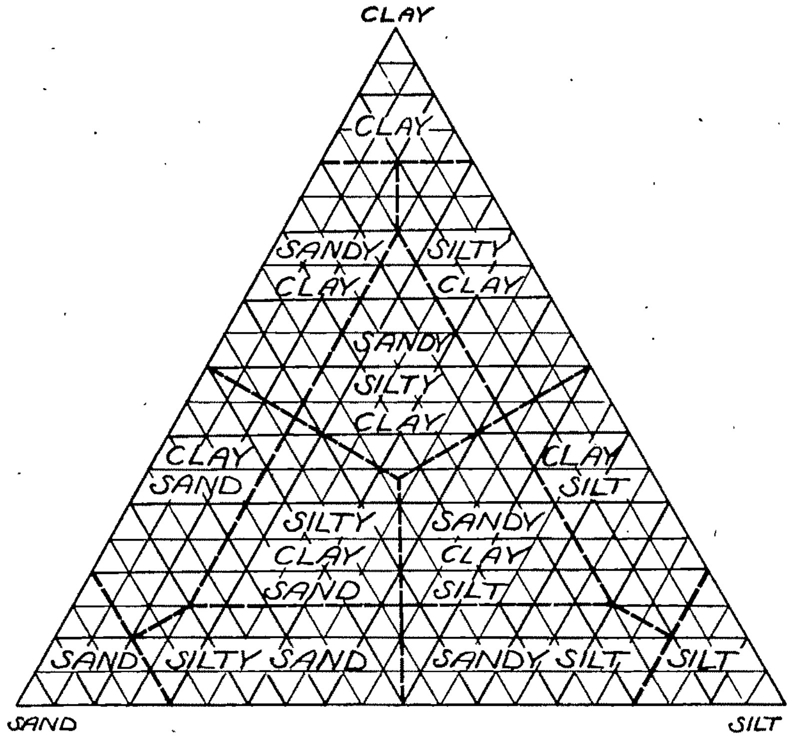

Figure 4. Proposed Soils Classification Triangle.

CONSOLIDATED SEDIMENTS

The names of the principal consolidated sediments are well established. The three principal groups are sandstone, shale, and limestone. There are, of course, many gradations and rocks of intermediate composition. A convenient classification (Trefethen, 1947, p. 67) which introduces no new nomenclature but which defines quantitatively the rock classes com-

prised of these three principal sediments and their mixtures is given by figure 5. In this diagram the divisions of the triangle are similar to those of the triangle for the unconsolidated materials (fig. 4), and the naming of the subdivisions strictly analogous. The field of carbonate rock (limestone, dolostone, or magnesian limestone) has been restricted to include only rock 85 percent (or higher) carbonate in order to accord with the purity requirements of many commercial uses of limestone or dolostone. The names are in harmony with established geologic usage.

Many sediments, of course, are not included in this simple

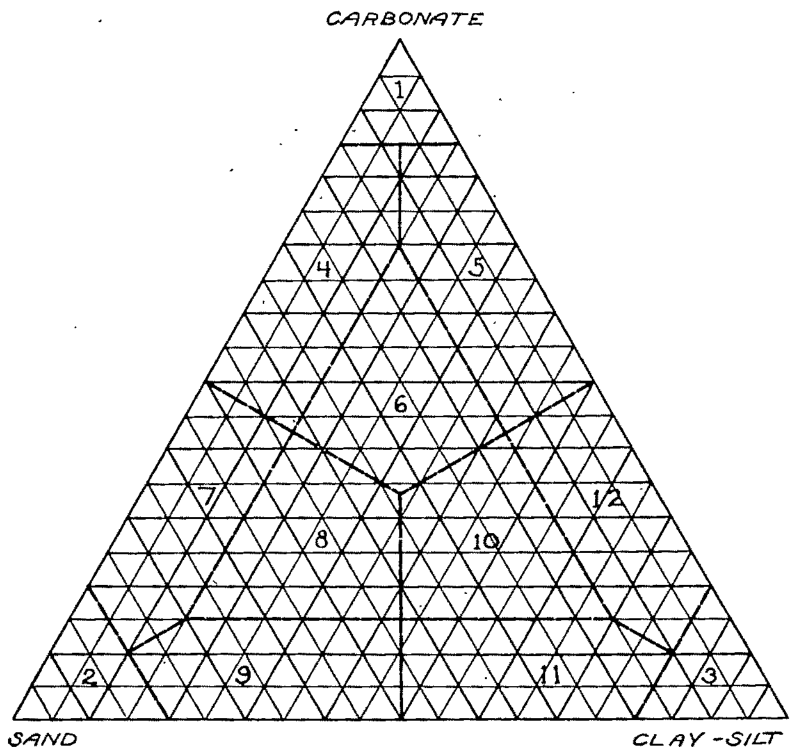

Figure 5. Classification Triangle for Sedimentary Rocks.

1 = limestone; 2 = sandstone; 3 = claystone, siltstone, or shale; 4 = sandy limestone; 5 = silty or argillaceous limestone; 6 = sandy, silty (or clayey) limestone; 7 = calcareous sandstone; 8 = calcareous, silty (or clayey) sandstone; 9 = silty or clayey sandstone; 10 = sandy calcareous claystone or siltstone; 11 = sandy siltstone or claystone; 12 = calcareous siltstone or claystone.

scheme, but it does include the most abundant types and serves as a basis on which other classifications can be superimposed. This classification has the advantage of placing definite limits for the groups for which mechanical analysis can be conveniently made by microscopic or other means. It also guides field nomenclature where approximations of mechanical composition must suffice.

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GEOLOGY IN TENTH CENTURY ARABIC LITERATURE

RUSHDI SAID

ABSTRACT. The Discourses of the Brothers of Purity, an Arabic classic written in the tenth century in Basra, includes remarkably modern geological ideas. An excellent and perfectly acceptable metamorphic cycle is described. The Discourses also contain the earliest known mention of peneplanation, pond evolution, epicontinental seas, weathering, and erosion and transport by streams and the wind.

RECENTLY my attention was drawn to some remarkably modern geological ideas in the classical Arabic work "The Discourses of the Brothers of Purity," the *lautern Brüder* of the German orientalists (*Ikhwan es Safa*). This work was written in Basra by a group of unknown scholars and intellectuals. According to most recent researches, it is almost established that the work was written between the years 941 and 982 A. D. (Disouki, 1947). This work has long been one of the standard classical works of the Arabic language studied in orthodox centers of learning as a piece of Arabic literature and a good sample of Arabic rhetoric and composition.

The Discourses is a voluminous work of four volumes which consists of separate discussions of "mathematical, physical, psychological, and metaphysical subjects" (vol. I, p. 2).[1] In its treatment of wide and varied fields of knowledge, the work differs but little from other works of the Middle Ages of early naturalists and scholars in Europe. It does differ, however, in containing a relatively larger amount of reasoning and smaller amount of fancy.

The work has received attention among modern orientalists and "*Morganland*" enthusiasts and parts of it have been translated into various European languages. It was commented upon in the excellent treatise of Dieterici (1881), with a good essay of the philosophy of the Arabs at that period. Dr. Dieterici (1879) has edited and translated the zoological part of it into German. Dr. Dowson (1869) has translated the same part into English from a Hindustani edition.

It is unfortunate that this part, which is the poorest and most fantastic of the whole work, was chosen for translation, whereas the other important parts were not translated, and hence did not find their way to the intellectual Westerner.

[1] Ikhwan es Safa (in Arabic) Bombay, 1305-1306 Hegira.

It became almost a tradition among writers on the history of science to mention scantily, hastily and with little appreciation the contributions of the Arabs, a tradition which probably had its origin in the days when feuds were continuous between "East" and "West." As far as the writer is aware, no mention of the Discourses has been noticed in any treatise on the history of science. Zittell (1899) devotes a few lines to the contributions of the Arabs and mentions Avicenna and Avirros. Adams (1938) also mentions Avicenna in several parts of his book but does not attempt to go further. Nordenskiöld (1944) devotes a chapter to the "Biological Sciences among the Arabians" in his book. He lists certain important works, but fails to mention the Discourses.

The Brothers of Purity were apparently a group of intellectuals who decided to "examine all the bodies of the world, to search for their beginnings, the reason for their existence and their organization, and to decipher the relationships between their effects and causes" (vol. I, p. 126). Appearing at a period of political unrest and corruption, the Brothers belonged to the Shiah, a minority in the Abbaside Empire which was dominantly Sunna. They antagonized the ruling circles and challenged their rule. This was the reason why they kept their organization secret and their writings concealed.

In their Discourses the Brothers mention frequently and with great admiration the Greek philosophy believing that "when Moslem theology is supplemented with Greek philosophy, perfection occurs" (vol. I, p. 24). The whole work was written in an atmosphere of extreme liberty and with a mind that is neither restricted by theological belief nor bound by tradition. In their discourse on geography their imagination and deduction goes so far as to speak of the continents as floating over the ocean "as an egg immersed in water" (vol. II, p. 51), thus crudely foreshadowing the modern idea of isostasy.

The following is my translation from the Arabic edition of 1305-1306 Hegira published in Bombay, vol. II, pp. 63-64.

"and know ye my brethren that the seas are like the swamps on the surface of the earth, and that mountains are like the bergs that separate the seas from each other, so that the whole surface of the earth is not covered by water. If there were no mountains on the earth's surface, and its face were rounded and smooth, the sea water would extend over the earth's face,

covering it completely as the atmosphere covers the whole earth, which would then be a sea. But the merciful care of God and his divine wisdom saw to it that parts of the surface of the earth were uncovered so as to be the habitation of the land animals, grass, trees, and crops, as these latter constitute the food of the animal and the substance of his body, and this is the prudence of the Dear and the Omnipotent.

"And know ye my brethren, that all valleys and rivers begin from mountains and hills, run in their courses and finally flow to the seas, swamps, and lakes. The excessive heat of the sun, moon and stars through the long ages and times will dry the moisture of the mountains increasing them in solidity and hardness. Then the mountains will break and disintegrate, particularly during storms, becoming boulders, pebbles and sands. The rain torrents will bring these pebbles and sands to the bottoms of the valleys and rivers and carry them, by their strong flow, to the seas, lakes, and swamps. The sea, because of its strong waves and great turbulence, will distribute these sands, muds and pebbles along its bottom, layer above layer, through the passage of time and ages. These will accumulate one above the other and harden, and then mountains and hills will rise from the bottom of the sea, as sand dunes in the deserts accumulate by the action of wind.

"And know ye my brethren that when the sea becomes closed because of these mountains and hills which we mentioned originating on their bottom, the water rises and extends over the coasts to the prairies and open land which are thus covered by water. This will go on through the passage of time, until the place of the prairies becomes the site of the sea, and the place of the sea becomes land. Then again the mountains disintegrate, becoming boulders, pebbles and sands, which material will be brought to the valleys by the action of rain. The rivers, by their flow to the sea, will carry and settle them on the sea bottom as we mentioned. The high mountains will thus be lowered until they will be levelled with the surface of the earth. The hardening of the sands and muds at the bottom of the sea will cause mountains, hills and dunes to form. The water then drains away from that area until these mountains appear and the hills are revealed, becoming islands and prairies. The remainder of the water remains in the lower places as lakes, lagoons, and swamps in which bamboos and weeds will grow.

The torrents will continue carrying the sand and mud until these places become dry. Trees, bushes, and grass will grow, and the place will become the home of lions and wild animals. People will go to it for timber, game and other things. Later these places become the sites for agriculture and crop growing. Villages and cities will develop and people will live there."

Again it must be emphasized that these ideas were written in the tenth century, some six hundred years before any speculation of a similar kind in Europe. Most remarkable is the fact that this is one of the earliest records, if indeed not the earliest, in which the idea of the inundation of the land by the sea is arrived at by pure logic rather than by assuming it from the finding of fossil shells in the interior—a line of reasoning which did not enter geological science until relatively recently, in fact as recent as the nineteenth century. The idea of peneplanation is beautifully set forth and outlined and seemingly is recorded for the first time in the history of geology. The next known reference to the peneplain is in Hutton's "Theory of the Earth," eight hundred years later. The evolution of the pond is remarkably modern and completely acceptable.

Although many of the Arab works were translated into Latin in the twelfth and thirteenth centuries, by order of certain European monarchs, the Discourses of the Brothers of Purity remained unknown to Western scholars until relatively recently.

It should be remembered that the Brothers movement has influenced tremendously Arab thinking for many centuries, and they must receive credit for paving the way for the great Arab thinker, Avicenna.

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REVIEWS

Sweeper in the Sky: The Life of Maria Mitchell, first woman Astronomer in America; by HELEN WRIGHT. Pp. vii, 253; 8 figs. New York, 1949 (The Macmillan Company, $4.00).—The first woman astronomer in the United States, Maria Mitchell, emerges in this biography as a woman with a strong personality and impressive accomplishments in different fields. Her discovery of a comet in 1847 brought her international fame, and focussed the attention of many on her intellectual qualities. These included the ability and perseverance necessary to acquire with little formal education a high degree of competence in astronomy and mathematics that qualified her to be first computer for the Nautical Almanac Office, and later professor of astronomy and director of the astronomical observatory of Vassar College at its founding in 1865. At Vassar College she proved herself a teacher of exceptional ability.

Her early life on isolated Nantucket Island in surroundings of rigid Quaker discipline and her active leadership in the woman's rights movement during the last twenty years of her life are important parts of this biography. Of interest also are the quotations from astronomical note books of Maria Mitchell which illustrate her keenness as an observer and as an interpreter of astronomical observations. Some of these observations appeared in THE AMERICAN JOURNAL OF SCIENCE in the years 1868-1879.

Notwithstanding earlier destruction of important source material, the author has written an admirable biography based on first-hand information collected in numerous centers. DIRK BROUWER

Principles of Mechanics; by JOHN L. SYNGE and B. A. GRIFFITH. New York, McGraw-Hill Book Co., pp. 530 + xvi. Second edition, 1949.—The first edition of this successful text appeared in 1942. There have been but a few changes for this second edition. Among the new features are a complete revision of the treatment of a charged particle in an electromagnetic field and a greater emphasis on units and dimensions. The book consists of two parts of about equal length. Part I covers plane statics and dynamics and is a complete text in itself. Part II treats mechanics in space, with chapters on Lagrange's equations and on the special theory of relativity. A logical, modern touch is a section on electron optics.

This is obviously a book written by mathematicians, not engineers. There are numerous problems, but only a few are numerical, and practical engineering units are not employed. Also, physicists

and engineers in this country commonly use F, a and v for force, acceleration and velocity rather than the P, f and q found in this text.

The coverage of the subject of analytical mechanics in this book is quite complete and with the use of a wide range of mathematical methods. Before tackling it the reader should have a fair knowledge of the calculus, elementary differential equations and analytical geometry. The qualified, interested student will obviously be well grounded in the subject after intensive study of this book.

WILLIAM W. WATSON

Dissociation Energies and Spectra of Diatomic Molecules; by A. G. GAYDON. New York, John Wiley & Sons, 1947. Pp. 289 + xi. 89 figures and 4 plates. $5.00.—The dissociation energies of diatomic molecules can be determined with great precision by spectroscopic methods. These energies are of importance for the chemist, for by combining them with thermochemical measurements the heats of formation of polyatomic molecules can be calculated and the strengths of various chemical bonds are made known.

This book, written by an investigator who has contributed much to the proper analysis of many molecular spectra, is a rounded account of the modern quantum mechanical theory relevant to the determination of dissociation energies. There are also chapters on the measurement of these energies by thermal methods and by controlled electron impact. In the last chapter numerical data are collected for about 250 diatomic molecules. The table of references seems to be complete. This is certainly an authoritative, well-written reference book on a subject of fundamental importance in chemistry.

WILLIAM W. WATSON

Radioactive Measurements with Nuclear Emulsions; by HERMAN YAGODA. Pp. x + 356, 48 plates, 27 figures. New York, 1949 (John Wiley & Sons, Inc., $5.00).—Dr. Yagoda has chosen to survey a field which is presently in a state of most rapid development. Such a situation provides an author with the opportunity so to present the classical work, as greatly to stimulate his readers, most especially those in fields to which the developments in question are only just penetrating. In this respect, Dr. Yagoda appears to have been eminently successful. Undoubtedly some of this stimulation is the inevitable result of drawing together and critically evaluating, related studies from so many different fields, but one feels that most of the credit is due to the author's thorough first-hand familiarity with most phases of his subject and to his very pleasant presentation.

The technical descriptions, while seeming in some cases unnecessarily elaborate, are very clear, and will be welcome to beginners in each field. The illustrations, though by no means over numerous, are well chosen, and appear well produced. While no section will prove profitless to any reader planning work with radioactivity, the section on reactions of emulsions seemed to this reviewer especially well done, as well as being outstandingly timely for workers in autoradiography.

It seems, in view of all this, ungrateful to discuss what seem to be mistakes of omission, and the author has further disarmed the reviewer by stating in his preface that "an expert . . . will doubtless feel that his . . . specialty has been presented in a most elementary fashion." In two cases, however, the opportunity has been neglected for detailed consideration of techniques which have tremendous possibilities for the future. One of these is the study of electron tracks, which are of great importance to workers with β-ray producing isotopes, and about which the physicists must have a great deal of isolated data, both from cloud chamber and photographic study. In the other, this reviewer was disappointed by the very brief reference to the use of radioactivity as a tool in chromatographic separations. We might well have been treated to a thorough discussion of the extraordinary sensitivity which this aspect of radiochemistry provides, as well as to a discussion of the comparative promise of photographic and counter methods of analyzing the radioactive spots or bands. It seems evident that photographic localization will permit revelation of as few as 10^7 molecules where labeled with short half-life tracers. Since subsequent discussions indicate familiarity with Leblond's technique of integral section and emulsion mounting, and since Evans' method may be taken as a direct adaptation of Yagoda and Endicott's contribution to the achieving of intimate permanent contact between section and emulsion, it is strange that these methods for β-particle autoradiography, are not discussed on a plane with the much less sensitive and precise, contact or focussing methods. It appears not at all uncommon to achieve 4μ localizations by either Leblond's or Evans' methods, using suitable emulsions, grain size being the limiting factor.

A very small number of actual errors of fact, must also be noted. On page 6, the statement is made that "optical-type emulsions . . . do not record individually resolvable tracks," when already citation has been made of numerous early demonstrations of alpha tracks, recorded on what must be considered optical type emulsions. On page 218, the statement is made that "in general . . . the difference in mass between tracers and stable atoms is less than 1 per cent," whereas the most casual examination of table 24 on the facing page,

shows that lanthanum 140 is the lightest element cited, of which this statement is true. This discussion would also have profited greatly from a reference to the rapidly accumulating body of information on the quantitative mass effects to be expected in biological and chemical use of tracers.

On page 20 the statement is made that "of the synthetic radioactive isotopes only those of the transuranium elements emit alpha particles." This cannot be considered an accurate preliminary to the discussion on page 205, of the tracer studies with astatine.

Such criticisms will serve only to emphasize the fact of the general excellence of this book which will prove a constantly useful tool in the hands of physicists, chemists, mineralogists, engineers and biologists. V. T. BOWEN

Carotinoide; by PAUL KARRER and ERNST JUCKER. Pp. xii, 388. Basel, 1948 (Verlag Birkhäuser, Swiss Francs: 48.-). More than twenty-five years have passed since the first appearance of Palmer's classical monograph on carotinoids and related pigments. Since then the study of these important pigments has undergone a phenomenal growth which brought with it the elucidation of the structure of most of the known carotinoids and the beginning of an understanding of their biological significance. A wealth of information has been presented in scores of publications, an "embarrassement de richesse," which has left the non-specialist frequently bewildered and discouraged.

Specialists and non-specialists alike owe a debt of gratitude to the authors of the present book, which presents an intelligent, up-to-date survey of this important field in a logical and eminently readable manner. The chemists will appreciate the chapters devoted to the chemistry of these compounds, to the elucidation of their structures, to the relations between color and constitution and to the numerous discoveries of general interest which are the by-products of such studies. They will share the regret of the authors that the manuscript was completed just prior to the adoption of a new nomenclature for carotinoids.

It would be a mistake to regard this book as one written primarily for chemists. Any biologist interested in biochemical relationships will want to see this book on his reference shelf. He will find in it a most extensive survey of the occurrence of carotinoids in plants and animals. The magnitude of this survey is best illustrated by the fact that the special index of names of plants and animals contains more than thirteen hundred items. In surveying critically such wealth of information an interested biologist might well discover biochemical relationships which have so far been

overlooked. In case the reading of the pertinent chapters should awaken in him the desire to carry out studies in this field, he will find the necessary techniques adequately described. The numerous colored plates illustrating the color and shapes of carotinoid crystals and the wealth of absorption spectra should prove to be of invaluable aid to him in the identification of the products isolated from biological material.

The book is handsomely bound, and the quality of the paper and printing is excellent. It is a book which many a scientist, once he has seen it, will want to possess. WERNER BERGMANN

Natural Products Related to Phenanthrene; by LOUIS F. FIESER and MARY FIESER with a chapter on the stereochemistry of the steroids by RICHARD B. TURNER. Pp. xii, 704. Third edition, A .C. S. Monograph No. 70, New York, 1949 (Reinhold Publishing Corp., $10.00).—The present monograph represents a greatly enlarged and revised issue of the previous editions [for the reviews of those editions see This JOURNAL, vol. 32, [5], p. 73 (1936), vol. 33 [5], p. 476 (1937)]. This edition has eliminated certain sections and chapters such as the chemistry of phenanthrene itself, carcinogenic hydrocarbons and triterpenoid sapogenins which appeared in the earlier editions and brings together under one cover an up to date and comprehensive survey of the natural products of the hydrophenanthrene series.

The book is divided into ten chapters, the last eight of which are devoted to the steroids. Chapter I deals with the naturally occurring phenanthraquinone pigments and the opium alkaloids, while Chapter II reviews the chemistry of the resin acids and the methods of synthesis of the alkylphenanthrenes.

The subsequent chapters lead the reader into and safely through that complex, vast and formidable maze of accumulated information that constitutes the present knowledge of the steroids. The authors deserve the highest commendations for the organization, conciseness and clarity with which each argument is presented and developed, and which could have resulted only from the perfect blending of a remarkable talent for writing, a profound knowledge of the literature and from their own experimental researches in the field. Moreover, Professor Fieser does not limit himself to that which is presently in the literature, but includes his own stimulating speculations on numerous, yet unsettled problems. Thus, for example, he proposes a revision of the structure of the toad poison bufotoxin and presents some very attractive evidence in its support. Of particular value are those sections which present the application of spectroscopy and optical activity in the elucidation of structural details.

Though the work is addressed primarily to the organic chemist, it should prove invaluable to the biochemist and the medical research worker as well, since the physiological action and metabolism of the important steroidal vitamins, hormones, cardiac active principles and alkaloids are generously reviewed. The monograph is replete with references through November 1, 1948, and to some papers that are still in press. Physical constants are reported for a total of 672 compounds, and in many cases yields and reaction conditions are indicated. The book is singularly free of typographical errors, this reviewer having found but four very minor errors.

ALFRED H. FRYE

Biochemical Evolution; by MARCEL FLORKIN. Pp. vi, 157; 25 figs. New York, 1949 (Academic Press, Inc., $4.00).—In this book Marcel Florkin has gathered together a vast amount of information which demonstrates quite clearly that there exists a biochemical differentiation in animals in many ways as distinct as but closely related to, morphological differentiation. He discusses adaptations and variations of many biochemical systems, but places special emphasis on respiratory function and osmoregulation. The section entitled "domain of glucemia" is especially well presented as are the other sections dealing with Florkin's own work.

It is unfortunate that the book is not well organized and at times difficult to follow, but biochemists and biologists will find it interesting reading. Much of the material is otherwise accessible only with difficulty and many of the conclusions are very fascinating.

EVA M. LOW

The Ocean (F. D. OMMANNEY, Oxford University Press, 1949, 288 pp.) is intended primarily for the general reader but is sufficiently detailed to provide background information for specialists in other fields of science. It is principally a book on marine biology, with chapters on plankton, the life of the sea shore, the bottom fauna of the continental shelf (and coral reefs), the animals and bottom deposits of the great depths, fisheries, and whaling. There is a brief preliminary outline of the nature of the ocean basins and of the general subject matter of physical and chemical oceanography and a final chapter of instruments and methods. Ommanney is authoritative in describing the animals and plants of the sea and their life habits. He is less secure in matters of physiology, population dynamics, and physical and chemical oceanography. The result is a curious compilation containing errors, misleading phraseology, and some poor judgments on controversial subjects. This is a minor criticism in that the objectionable part of the book is a

small fraction of the whole, but it is unfortunate that the author permitted himself a wider scope than his capabilities warranted. *The Ocean* is similar in approach to an earlier book, *The Seas* by Russell and Yonge, that is generally regarded as the oceanographic classic for the popular reader. Ommanney's book has the obvious advantage of including some recent findings, but it is vastly inferior to the earlier work in readability and accuracy. GORDON A. RILEY

Das Geheimnis der Kristallwelt; by H. TERTSCH. Pp. 391; 12 plates; 48 figs. Vienna, 1947 (Gerlach and Wiedling). This exceptionally well-indexed history of the development of physical mineralogy and crystallography should find a warm welcome in all mineralogical libraries, and in the libraries of all others interested in the development of the physical sciences in general. The author enthusiastically describes mineralogy as the mother of practically all the natural sciences, responsible either directly or indirectly for many of their fundamental advances. The names crystallography and mineralogy are used almost interchangeably throughout the book, though the meaning is usually restricted to physical mineralogy. Systematic mineralogy and other branches of the science are covered briefly, but the principal emphasis is always on mineralogical crystallography in the broadest sense. The treatment of the development of optics, crystal morphology, crystal structure, and certain fields of modern physics basic to these, is complete. Names of many great physicists are brought into the discussion and their contributions outlined, always in relation to the crystallographic theme of the book. An interesting and effective device is the printing of all important names in large capital letters. Scarcely a page can be found without several; 28 pages of indices help to locate both names and subjects easily. The reviewer is particularly grateful for the thorough indexing of this book, for its usefulness as a reference is thereby greatly enhanced. HORACE WINCHELL

Physical Geology; by CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT, 3rd Ed. Pp. xv, 602; 365 figs. New York, 1948 (John Wiley and Sons, $5.00).—The first and second editions of Physical Geology are very well known and have been widely used as textbooks in many American colleges and universities. The third edition, while inproved by many new illustrations, one new chapter, and revisions of parts of many chapters, is still essentially in major organization and form of treatment, the same book, so well known to most teachers of geology.

To acquaint beginning students "with the major goals, the methods, and basic outlines of a vast and unfamiliar field of knowledge"

the authors have added a new unit, Chapter 2, on the method and scope of geologic study, a highly desirable addition. While the relations between internal and external forces of the earth are briefly discussed and the concept of geologic time is introduced, methods of obtaining geologic data are not fully explained. A more complete comparison between the methods of the various sciences would be helpful. One of the distinctive features of geology which should be pointed out is the importance of spatial relationships and the use of maps to express them. Much of physics and chemistry is expressed in the symbolic language of mathematics, whereas in geology cartographic symbolism is the medium used to express surface forms, the distribution and structure of rocks, and paleogeography. If maps, sections, and block diagrams represent the chief media to express geologic relationships this is important and should be emphasized early in a student's acquaintance with the subject.

Changes have been made in almost every chapter, only a few of which can be mentioned here. The relation of velocity to erosion and transport has been restated (pp. 78-79) but ambiguity still remains since velocity is not defined and it is apparently used in two senses, for, as Quirke[1] has pointed out, velocity in the Chezy formula, $V = B\sqrt{rs}$,, is that of the unencumbered stream and, as Rubey[2] has emphasized, the diameter of the largest piece of rock the stream can push along its bed is a function of the "bed" velocity. In this section a graph showing a typical vertical velocity curve would be helpful. Several new diagrams after Bagnold (p. 211) illustrate the formation of sand dunes. A new section of Chapter 19 outlines a possible history of mountain ranges including the formation of a batholith by remelting in the lower part of the thickened shell. The possible relationship of island arcs to mountain building is not mentioned. The important material on minerals, rocks, and maps in the appendices seems not to have been altered significantly. Many new titles appear in the lists of reading references at the end of the chapters.

The stimulating conferences in the training of geologists held under the leadership of Professor Longwell at various society meetings of recent years attest to the fact that geologists everywhere are reappraising the teaching of geology. At the same time at many colleges the teaching of science for the general student has been reviewed. The following general comments and questions are in part

[1] T. T. Quirke, 1945. Velocity and load of a stream: Jour. Geol., vol. 53, p. 181.

[2] W. W. Rubey, 1938. The force required to move particles on a stream bed. U.S.G.S. Prof. Paper 189-E, p. 121.

stimulated by some of these conferences and discussions and are offered even though they apply no more to this book than to other textbooks in geology and if they are valid criticisms indict the teachers (including most definitely this reviewer) as well as the textbooks. The sciences of physics, chemistry and biology have met at the atom and, perhaps as a result, a large body of common material is included in modern elementary textbooks of both chemistry and physics. Some biology texts also include fairly extensive summaries of fundamental physics and chemistry. No trend toward the other sciences is evident in the geology textbooks. It is true that many terms and laws of physics are used or referred to but they are rarely defined. Geology as represented by its beginning textbooks seems to have moved away from the use of mathematics and of graphs. Many relationships explained in words could be better shown graphically; for example, vertical and horizontal distribution of velocity in streams, relation of temperature to depth, and effect of pressure on melting points of rocks. (Photographs however have both increased in number and vastly improved in quality in the last twenty-five years.) Few beginning textbooks of geology reflect in their discussions of minerals the revolution in mineralogy since the widespread use of X-rays. If physical geology is, as many say it is, the application of the principles of physics and chemistry to the Earth, should not a beginning textbook state those principles and indicate clearly where they apply to geology.

JOE WEBB PEOPLES

Historical Geology; by CARL O. DUNBAR. Pp.xii, 567; profusely illustrated. New York, 1949 (John Wiley and Sons, $5.00).—This book presents an authoritative and well documented, lavishly illustrated story of earth history written in clear and vivid language by one of the masters of historical geology. To quote its author, it is "a successor to, and an outgrowth of, the *Textbook of Historical Geology* by Schuchert and Dunbar." Although it preserves the same point of view and in general the same organization as its predecessor, it is in several important respects a different and improved work.

The book is divided into five parts: I. Prologue, II. Before the Cambrian, III. The Paleozoic World, IV. The Mesozoic World, and V. The Modern World Unfolds. At the end of the book is an appendix: An Introduction to Animals and Plants, which will be helpful to students in their laboratory work on fossils, and an adequate index.

The text, which has been largely recast, in part to take account of advances in knowledge, speaks more clearly and dramatically than the old. The illustrations have been greatly improved by increasing

the size of the paleogeographic maps, introducing many large "bleed cuts," and replacing some seventy figures with new photographs and drawings. References and collateral reading lists have been carefully revised to include the most recent publications. An especially commendable feature is the addition of numerous foreign examples and references which give the new text a more international character than that of its predecessor.

As would be expected of Professor Dunbar, this book, like its several predecessors, strongly emphasizes the biological side of historical geology, perhaps to some extent at the expense of other aspects. However, there are abundant paleogeographic and geologic maps and geologic cross sections, considerable emphasis on stratigraphy, adequate discussions of orogenies, and brief references to economic products. One prominent omission, that of the dozen correlation tables appearing in the older volume, seems fully justified. These were omitted because they were felt to be too technical for the student and inadequate for the teacher. Those teachers who desire the details of correlation can secure them from the several charts that have been issued by the Committee on Stratigraphy of the National Research Council.

Exceptionally useful to both student and teacher are fifty or more geologic sections and some twenty-five thumbnail geologic maps. Most of these appeared in the previous volume but they have been redrawn in many cases and are sharper and more legible in the new book. Noteworthy are those showing deltaic complexes and regional lithological variations. There is a wealth of lantern slide material in these drawings and no doubt they will be exploited for this purpose.

The thirty-eight new paleogeographic maps, based on Professor Schuchert's latest unpublished work, are more than twice as large as those used in the earlier volume and are a vast improvement. Discerning readers will note that the lettering and other symbols on these are now clear and legible and will probably smile indulgently at the wind-swept clouds that so strategically cover areas of uncertainty.

The seventeen plates of invertebrate fossils bring together for convenient reference and comparison the more common and characteristic genera of the Paleozoic and Mesozoic rocks. These are apportioned as follows: Cambrian (3), Ordovician (2), Silurian (1), Devonian (2), Mississippian (1), Pennsylvanian (1), Permian (2), Triassic (1), Jurassic (1), and Cretaceous (3). The plates are supplemented by a host of text figures. Unfortunately for the student there are no plates and almost no text figures of Cenozoic invertebrates—an omission that might mislead the student into assuming

that "the time of the great dying," as Walther called the close of the Cretaceous, marked the finish of most of the invertebrates. The great variety and abundance of Cenozoic protozoans, reef corals, echinoids and mollusks is thus little emphasized, whereas the vertebrates receive what some may consider an unusually large amount of attention.

This reviewer was pleased to find that the author retained the pictures of Smith, Murchison, Lyell, Logan, Chamberlin and Walcott. These bewhiskered gentlemen serve to remind us that some of the fundamental principles of geology were formulated by investigators who, lacking modern instruments and devices, used their legs and imagination instead.

Historical Geology will be welcomed by students and teachers alike, and intelligent laymen will find the story of earth history so vividly and clearly set forth that they can grasp the essential points readily. Professor Dunbar is to be congratulated for an excellent work and the publisher is to be commended for a product of the highest quality. ROBERT R. SHROCK

Landscape, As Developed by the Processes of Normal Erosion; by C. A. COTTON. 2d Ed. Pp. 509; 375 figures. Christchurch, New Zealand, 1948 (Whitcombe and Tombs, Ltd.).—The appearance of a second edition of Professor Cotton's excellent treatise, first published in 1941, should be a source of gratification not only to its author but also to all those who have found in the book a lucid and comprehensive treatment of the sculpture of the land by streams and processes of mass-wasting.

An able and admiring follower of W. M. Davis, Cotton has set forth in systematic fashion the facts and theories of this central aspect of geomorphology, illuminating them with the results of a lifetime of observation and study. Taken together with its companion volume, *Climatic Accidents*, this book constitutes the most extensive general work on geomorphology in the English language.

Although written by a geologist who has spent most of his active professional life in New Zealand, the volume is not insular in its approach. On the contrary it draws its literature, its examples, and its illustrations from all the continents of the Earth, and can be as useful in Britain or North America as in the antipodes.

The general organization of the Second Edition is much like that of the First, but the discussion has been considerably amplified and the overall length increased. The paper and halftone illustrations have been vastly improved, thanks no doubt to the ending of wartime restrictions, and the landscape sketches and block diagrams for which the author is deservedly famous are present in satisfying quantity.

Not only the advanced special student but the geologist whose interests are more general will find this a very useful book, for, as Cotton truly says in the preface, "a reasoned understanding of geomorphic processes is a necessary part of the equipment of a geologist for the interpretation of geological history."

The close reader of the book will find that statement amply justified. RICHARD FOSTER FLINT

The Importance of Upwelling Water to Vertebrate Paleontology and Oil Geology; by MARGARETHA BRONGERSMA-SANDERS. Verh. konkl. Nederlandsche Akad. v. Wetenschappen afd. Natuurkunde, Vol. 45, No. 4, pp. 1-112, 7 text figs. Amsterdam, 1948.—In spite of its cryptic title this volume is packed with almost dramatic interest for stratigraphers as well as for paleontologists and petroleum geologists. It is concerned with the phenomenon of mass destruction of marine life such as that which occurred at Walvis Bay, South Africa, in 1948, and with its underlying causes and its effects on the bottom sediments.

The mass destruction at Walvis Bay occurred during a 8-day period in January, 1948, when fishes died and drifted ashore in almost incredible numbers. Such destruction has occurred repeatedly along this coast, commonly at intervals of a few years. Investigation of the shallow sea floor has revealed a so-called *azoic zone* along this coast in which the bottom sediment is greenish mud rich in H_2S gas, and in which there is almost no bottom-dwelling life except anaerobic bacteria. This zone is 25 to 30 miles wide, reaching from near shore out to a depth of nearly 500 feet, and it stretches for some 200 miles along the open coast south of Walvis Bay. Some previous students have believed that the periodic mortality to fishes in the overlying water is the result of liberation of the H_2S gas from the bottom sediment, but the author thinks this is a result rather than a cause of the mortality which she believes is due to toxic products in the water resulting from excessive growth of dinoflagellates, such as the one which produced the "red tide" along the west coast of Florida in 1945.

Such epidemics of dinoflagellates, she shows, depend on a rich supply of some of the minimal food elements in the sea, and upon relatively high temperature and quiet weather. These conditions are produced occasionally in the summer months along subtropical and warm temperate coasts where upwelling currents bring rich food supply to the surface. It is then that outbursts of dinoflagellates lead to mass destruction of marine life so that fishes and other organisms accumulate on the sea floor in vast numbers where there

are no scavengers or other benthonic organisms except the anaerobic bacteria that produce H_2S gas to keep the bottom muds poison and lifeless. It is important to note that the azoic zone along the west coast of South Africa is not landlocked nor separated by any physical barrier from the normal sea floor.

Upwelling currents produce optimum conditions for the growth of diatoms which, however, thrive in water somewhat cooler than that required by the dinoflagellates, and the bottom mud of the azoic zone is practically a diatomaceous ooze. Only an exceptional combination of a stretch of hot, quiet days in the midst of summer is able to tip the scales in favor of a sudden florescence of dinoflagellates. It is suggested that the diatomaceous shales of California were produced under conditions somewhat like that of the azoic zone along the west coast of South Africa, and that the occasional mass destruction of fish and other pelagic organisms provided important source materials for petroleum. CARL O. DUNBAR

Eocene Stratigraphy and Foraminifera of the Aquia Formation; by ELAINE SHIFFLETT, Dept. of Geology, Mines and Water Resources, State of Maryland, Bull. 3. Pp. IX + 93, 5 plates, 21 figs. Baltimore, 1948.—In its outcrop the Eocene series in Maryland rests on the Cretaceous and is succeeded by Miocene beds. Here it consists of 2 units, the Aquia formation of Wilcoxan age and the succeeding Nanjemoy formation of Claibornian age. Down dip, however, fossils recovered from wells 50 to 75 miles farther east have indicated an absence of both these formations and the presence of Paleocene and Jacksonian Eocene beds between the Cretaceous and the Miocene.

In order to understand this peculiar relation Miss Shifflett made a detailed study of the formaninifera in the outcrop belt of the Eocene and in the samples logged from numerous wells in eastern Maryland. As a result she has been able to demonstrate that the Paleocene beds appear as a thin wedge below the Aquia formation a few miles east of the outcrop and thicken to a maximum of about 100 feet within 40 to 50 miles. Beds of Jacksonian age likewise appear about 30 miles southeast of the outcrop and thicken down dip. On the contrary, the Aquia formation thickens down dip to a maximum of about 150 feet within 10 miles of the outcrop and then thins to a featheredge within 25 or 30 miles to the southeast. This suggests that an island existed in the area of eastern Maryland during deposition of the Aquia formation. Similar evidence indicates that the island persisted during the deposition of the Nanjemoy formation.

Physical relations are effectively illustrated in 21 text figures. About half of the volume is devoted to the systematic description of the Eocene foraminifera of Maryland.

This fine report convincingly solves a problem in stratigraphic relations that has long been the source of controversy, and that could hardly have been solved by any other technique.

CARL O. DUNBAR

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THE AGE OF URANINITE FROM GORDONIA, SOUTH AFRICA

ARTHUR HOLMES

WITH AN ISOTOPIC ANALYSIS OF LEAD

W. T. LELAND AND A. O. NIER

ABSTRACT. The age of uraninite from a post-Kheis pegmatite in Gordonia, South Africa, hitherto known only within wide limits (Holmes, 1934), is discussed afresh in the light of an isotopic analysis of lead separated from a sample previously analysed by Hecht (1934). From the apparent ages calculated from AcD/RaG, RaG/U and AcD/U respectively, the nature of the alteration of the mineral is inferred and the most probable age is found to be 1025 ± 10 m.y. The "age" calculated from ThD/Th is anomalous. It is shown that unsystematic discrepancies of this kind are usual in all fully investigated radioactive minerals, implying that Th and/or Pb have suffered differential loss or gain, or that Th has not been accurately determined, or both. Crude age estimates of post-Karagwe-Ankolean euxenite from Uganda and of post-Damara lepidolites from South-west Africa (Ahrens, 1949) suggest, as a working hypothesis, that the intensely folded sediments of the Kheis, Damara, Kibara, Urundi, and Karagwe-Ankolean Systems may all belong to a single orogenic belt extending from South Africa to Uganda.

ANALYTICAL DATA AND INTERPRETATIONS

IN 1934 I discussed in this JOURNAL the age of the Gordonia uraninite in the light of an analysis made by Mountain (1931) and of a series of analyses made by Hecht (1934) of two specimens, A and B, sent to me for investigation by the late Dr. Percy Wagner. Quite recently I discovered another analysis by Haller (Behrend, 1933) which had previously been overlooked. All the specimens of uraninite referred to were collected from the post-Kheis pegmatites of a desolate region of Pre-Cambrian rocks north of the Orange River, not far from the Aughrabies Falls, in the north-west of the Cape Province of South Africa (see fig. 2). The pegmatites and their minerals have been described by Mountain (1931) and Behrend (1933).

The analytical data are listed in table 1 together with the apparent ages read from the family of graphs prepared by Wickman (1944).

TABLE 1

Uraninites from the post-Kheis pegmatites of Gordonia

	Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent age in m.y.
A	10.46	57.09	9.04	.158	.86	1135
B′	10.21	55.00	11.75	.153	.82	1125
B	9.40	58.20	8.06	.142	.88	1015
B″	8.88	60.28	5.66	.135	.91	925
C	8.80	63.69	8.19	.122	.89	875
D	9.45	63.47	7.39	.133	.90	940

A. Uraninite, Back River. Composition of original sample (riddled with veinlets) calculated from analyses of A″ (HCl extract) and A′ (residue) by F. Hecht (1934, p. 340). A. Holmes (1934, p. 345).

B′. Megascopically fresh uraninite (S.G.=8.582), prepared from the original sample B by handpicking material free of visible alteration products. *Analyst:* F. Hecht (1934, p. 341).

B. Uraninite, Back River. Original sample, including veinlets (S.G.= 7.201) B=39.4% B′+60.6% B″. *Analyst:* F. Hecht (1934, p. 341).

B″. Altered residue of B after extracting B′. Calculated composition.

C. Uraninite, Bokspul Farm, Back River, about 5 miles above the confluence with the Orange River (S. G.=8.876). *Analyst:* E. D. Mountain (1931, p. 139).

D. Uraninite, Back River (S.G.=9.098). *Analyst:* H. Haller (F. Behrend, 1933, p. 19).

It will be seen that the range of the apparent ages is so wide that no close estimate of the real age can be attempted. In my 1934 paper I decided that Mountain's specimen C was the one likely to furnish the most reliable approximation to the true age, because of its relatively low H_2O and SiO_2 and high S.G. However, Behrend's specimen D is better still as regards SiO_2 and S.G.; H_2O, unfortunately, was not recorded. I described Wagner's specimen A as being "in the state of preservation described by Ellsworth as *poor*." The hand-picked material B′ appeared to be much more satisfactory, being of the standard rated by Ellsworth as *good*. It was therefore somewhat surprising to find that it gave practically the same high apparent age as A. Comparison of the data for B and B′ led me to conclude "that the material B′ has suffered a considerable loss of uranium, with consequent relative gain in thorium and lead."

Since the age of the Gordonia uraninite is of critical significance in connection with the correlation of the Pre-Cambrian orogenic belts of South and Central Africa (Holmes, 1949), it was clearly desirable that the matter should be fur-

ther investigated with the aid of an isotopic analysis. To this end I sent part of the remaining analysed powder of B′ to the Research Department of Imperial Chemical Industries Limited at Billingham, Co. Durham, where, under the supervision of the Chief Analyst, Mr. W. C. Hughes, a sample of pure lead iodide was prepared from it. The sample was then sent to Professor A. O. Nier for determination of the isotopic constitution of the lead. The purpose of this paper is to record and interpret the results made available by the active cooperation of Mr. Hughes and Professor Nier. It is a pleasure to take this opportunity to acknowledge my indebtedness to my two friends and those of their colleagues who shared in the work, and to thank them most cordially for their generous collaboration.

The results and the various "ages" calculated from them (Keevil, 1939) are set forth in table 2.

TABLE 2

Uranite, B′, from Back River, Gordonia

CHEMICAL ANALYSIS (By F. Hecht)

Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent age in m.y.
10.21	55.00	11.75	.153	.82	1125

ISOTOPIC ANALYSIS OF LEAD (By W. T. Leland and A. O. Nier)

Isotopic Proportions of Lead (Radiogenic)	Pb^{204} [1]	Pb^{206} 100	Pb^{207} 7.35	Pb^{208} 5.42
Per cent of Radiogenic Lead in Uraninite	—	9.054 RaG	.665 AcD	.491 ThD
	$\frac{AcD}{RaG}$	$\frac{RaG}{U}$	$\frac{AcD}{U}$	$\frac{ThD}{Th}$
Lead Ratios	.0735	.1646	.0121	.0418
Calculated Ages (m.y.)	1037	1148	1106	914

[1] Less than 1/20,000. Original lead is therefore negligible.

The spread of the three "ages" calculated from

RaG/U	AcD/U	and AcD/RaG
1148	1106	1037 m.y.

indicates that the handpicked uraninite B′ has, in fact, been altered, notwithstanding its appearance of freshness. Moreover, the numerical order of the "ages" and the intervals between them correspond to the pattern that would result from either loss of uranium or gain of lead. As shown by figure 1 the age calculated from AcD/RaG (1037 m.y.) is therefore the one that approximates most closely to the true age.

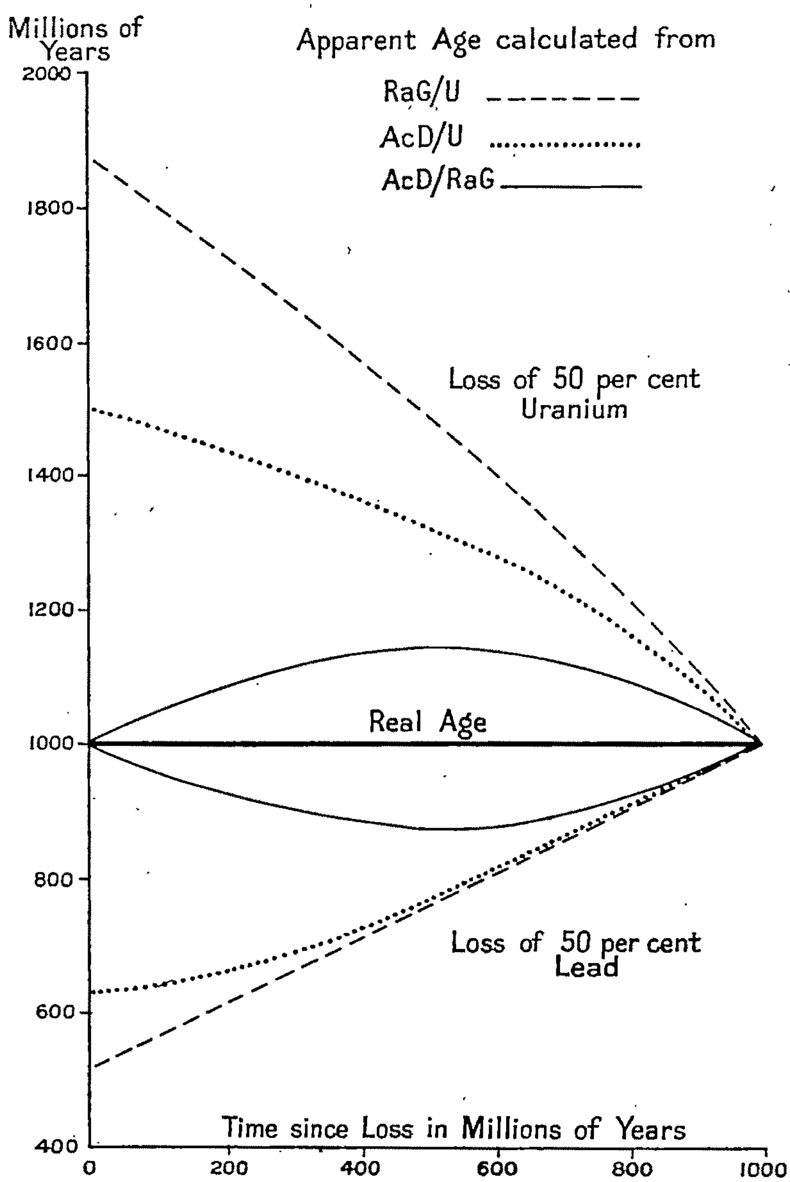

Figure 1. To illustrate the respective effects of loss of uranium and loss of lead on the apparent ages (calculated from ratios involving RaG and AcD) of a mineral of which the real age is 1000 million years.

Comparison of the analytical data for B and B′ (table 1) indicates that loss of U has been the dominant factor in the alteration of B′. We may begin by considering this factor alone. To bring the "ages" from RaG/U and AcD/U into agreement with 1037 m.y., U has to be raised to 61.4 per cent, implying that the lost U, thus arithmetically restored, may have been as much as 6.4 per cent of the mineral, or about 10 per cent of the original uranium content. Any allowance for gain of Pb would, of course, reduce these figures. If this loss had taken place about, say, 500 m.y. ago (cf. fig. 1) the age calculated from AcD/RaG would be nearly 30 m.y. too high. If the loss had occurred earlier or later, the error would become correspondingly smaller, becoming vanishingly small if the loss were recent.

Gain of Pb brings about a pattern of results similar to that due to loss of U, but with smaller departures from the real age. Here the age from AcD/RaG is again most nearly correct, but the maximum error—for alteration about 500 m.y. ago—is only 15 m.y. A combination of loss of U and gain of Pb would give intermediate results. Thus, so far as the effects of loss or gain of U or Pb are concerned, it may be concluded that if the alteration was recent the most probable age is 1037 m.y., whereas if the alteration occurred, say, in the Palaeozoic or earlier, the age would be slightly lower by an amount up to 15 $\sim$ 30 m.y.

The possibility should not be overlooked that B′ may also have suffered a slight loss of radon during its history. The effect of such loss would be that the mineral would now contain less RaG than it would have done if all the radon had been retained. Allowance for this possibility slightly decreases the value of AcD/RaG and therefore of the age calculated from this ratio. Again we reach the conclusion that 1037 m.y. is an upper limit and that the true age may be slightly lower.

As a check on this conclusion it is of interest to calculate the apparent ages of sample B on the assumption that its lead has the same isotopic constitution as that of B′. The results are set out in table 3.

Here the agreement between the "ages" based on RaG and AcD is unusually good, a result which is consistent with the assumption that there has been no appreciable loss or gain of the uranium-leads or of uranium. The numerical order of the

"ages," if it be significant at all, suggests a very small loss of either radon or the uranium-leads. The most nearly correct age in the former case would be 1015 m.y. calculated from AcD/U (a ratio not affected by loss of radon), while in the latter case it would be 1037 m.y. It would appear that the mineral B has remained a nearly closed system as regards the migrations of Pb and U, the respective loss or gain in B″ being compensated by a corresponding gain or loss in B′.

In the light of the above discussion the most probable age of the investigated sample of Gordonia uraninite may be stated as 1025 ± 10 m.y.

TABLE 8

Uraninite B from Back River, Gordonia

(assuming Pb to have the same isotopic constition as the Pb of B′)

CHEMICAL ANALYSIS (Table I, B)

Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent age in m.y.
9.40	58.2	8.06	.142	.88	1015

ISOTOPIC ANALYSIS (Table II)

Isotopic Proportions of Radiogenic Lead	Pb^{204} —	Pb^{206} 100	Pb^{207} 7.35	Pb^{208} 5.42
Per cent of Radiogenic Lead in B		8.336 RaG	.613 AcD	.452 ThD
	$\frac{AcD}{RaG}$	$\frac{RaG}{U}$	$\frac{AcD}{U}$	$\frac{ThD}{Th}$
Lead Ratios	.0785	.1432	.0105	.056
Calculated Ages (m.y.)	1037	1010	1015	1215

"THORIUM-AGE" ANOMALIES

It will have been noticed that the "ages" calculated from ThD/Th (tables 2 and 3) differ considerably from those based on the uranium-leads. Discrepancies of this kind are unfortunately the rule in practically all the minerals so far investigated with the aid of isotopic analyses (see table 4) and no general explanation for the anomalies seems to be possible. The fact that more of the anomalies listed in table 4 are negative than positive indicates that some improvement could be effected by an appropriate change in the value adopted for the disintegration constant of Th; but to be of any practical use in this connection the change required would be far too great to deserve serious consideration and,

moreover, large unsystematic anomalies would still remain. For the same reasons it can hardly be supposed that analytical errors in the determination of Th can be mainly responsible for the anomalies, though they may be partly so in certain cases. For the most part the anomalies can be referred only to loss or gain of Pb or Th or both, brought about as a result of migrations accompanying processes of alteration.

TABLE 4

"Thorium-Age" Anomalies

Mineral and Locality	*Most Probable age (in m.y.)*	*Apparent Age from ThD/Th*	*Anomaly (Apparent—Probable)*
1. Samarskite, Spinelli quarry, Conn.	255	266	+ 11
2. Thorianite, Ceylon	485	460	— 25
3. Uraninite, Bisundi, India	735	935	+ 200
4. Monazite, Soniana, India	735	613	— 122
5. Uraninite, Besner, Ontario	760	796	+ 36
6. Uraninite, Singar, India	910	1003	+ 93
7. Uraninite B′, Gordonia, S. A.	1025	914	— 109
" B, " "	1025	1218	+ 193
" B″, " "	1025	1620	+ 595
8. Uraninite, Parry Sound, Ontario	1025	956	— 69
9. Uraninite, Wilberforce, Ontario	1035	988	— 47
10. Cleveite, Norway	1075	842	— 233
11. Monazite, Mt. Isa, Queensland	1200	1000	— 200
12. Monazite, Las Vegas, New Mexico	1330	773	— 557
13. Monazite } Huron Claim	1985	1827	— 158
14. Uraninite } Manitoba	1985	1273	— 712

For data (except 3, 4, 6 and 7) see Nier (1939) and Nier, Thompson and Murphey (1941).

For other data and details of calculations see—

1. Holmes (1947).

3, 4. Holmes, Leland, Nier, and Smales (1949).

6. Forthcoming paper (Amer. Min.) by Holmes, Leland, and Nier.

7. This paper. The apparent ages for B and B″ are calculated on the assumption that the lead has the same isotopic constitution as that of B′.

9, 13, 14. Holmes (1948).

11, 12. Holmes and Smales (1948).

Positive anomalies imply differential loss of Th or gain of Pb (or relative gain of ThD).

Negative anomalies imply differential gain of Th or loss of Pb (or relative loss of ThD).

It should be noticed that relative loss or gain of ThD is not likely to be possible unless lead from one mineral migrates into another having a higher or lower Th/U ratio. It has been suggested that the lead generated from UO_2 or UO_3 probably behaves like PbO, in which case it would be less soluble than the lead generated from ThO_2 which may behave like PbO_2 or $(PbO_4)^{-4}$. But this hypothesis can have no application to a homogeneous mineral, because, as Wickman has pointed out to me, when the lead atoms are generated they must travel several thousand Å through the crystal lattice, quite haphazardly. The lead isotopes must therefore be well mixed throughout the period of their accumulation. Once mixed, no differentiation into a variety of lead relatively rich in ThD is possible by solution or other chemical processes. Diffusion would theoretically involve slight differentiation, but the atomic weights of Pb^{206}, Pb^{207}, and Pb^{208} are so close that the degree of separation effected by natural processes would be completely negligible.

Obviously each mineral for which data are available must be considered in the light of the relevant evidence; unfortunately the evidence is rarely adequate to provide an unambiguous solution.

In the case of the Gordonia uraninite B, the anomaly of which is positive, we have seen that there is no evidence of all-over introduction of the uranium-leads from an external source. It is therefore highly improbable that thorium-lead, ThD, could have been so introduced. In this case there is no alternative to the conclusion that B — and therefore the visibly altered material B″ — has lost Th. On the other hand the low thorium-age of B′ can only mean that this part of the specimen gained Th, and gained it in sufficient amount to overcome the effect of a small gain of Pb. It thus appears that Pb has been gained by B′ and lost from B″, the net effect being an all-over loss from B as a whole. Reduced to the simplest terms, the relevant effects of the alteration of the mineral can be schematically represented as follows:—

B		B″		B′
Th lost	⟵	Th lost	⟶	Th gained
		Pb lost	⟶	Pb gained
		U gained	⟵	U lost

This scheme is not strictly rigorous, as it does not express the slender indication, already discussed, that there may also have been on balance a very slight loss of lead and/or radon from B.

It is of interest to test the possibility that the migration of atoms of Th and Pb (expressed as atomic proportions) into B′ may have been responsible for the displacement of a corresponding uumber of atoms of U, which in turn migrated into B″,

Loss of U = U in B — U in B′ = 3.20%

Gain of Pb = Pb in B′ — Pb in B = .81%

Gain of Th = Th in B′ — the percentage of Th in B (9.62) which would correspond to an age of 1025 m.y., i.e. 11.75 — 9.62 = 2.13%.

The corresponding atomic proportions (x 100) are:

Loss of U = 1.34;	*Gain of Pb* = .39
	Gain of Th = .92
	1.31

If the fact that this atomic account very nearly balances is significant and not merely a coincidence, it suggests that the alteration was recent, and it provides an explanation for the fresh-looking appearance of B′. A simple metasomatic exchange of Th and Pb for U would not be expected to produce any megascopic symptoms of alteration in B′ such as are clearly visible in B″.

PROVISIONAL GEOLOGICAL CORRELATIONS

In Central Africa a well marked Pre-Cambrian orogenic belt extends from the west of Lake Victoria to the High Zambesi, where it disappears beneath the late Pre-Cambrian Katanga belt (fig. 2). Between Katanga and the Congo headwaters the older belt is represented by the sediments, intensely folded and in part metamorphosed, of the Kibara system (Robert, 1944; Cahan and Mortelmans, 1946). From the northern part of Lake Tanganyika the northerly continuation of the Kibara system is known as the Urundi System in the Belgian territories (Boutakoff, 1939), and as the Karagwe-Ankolean (K.-A.) system in Uganda (Combe, 1932). Granites and a highly distinctive Sn-W-Cb type of mineralisation characterize the belt at intervals throughout its length. So far, only one

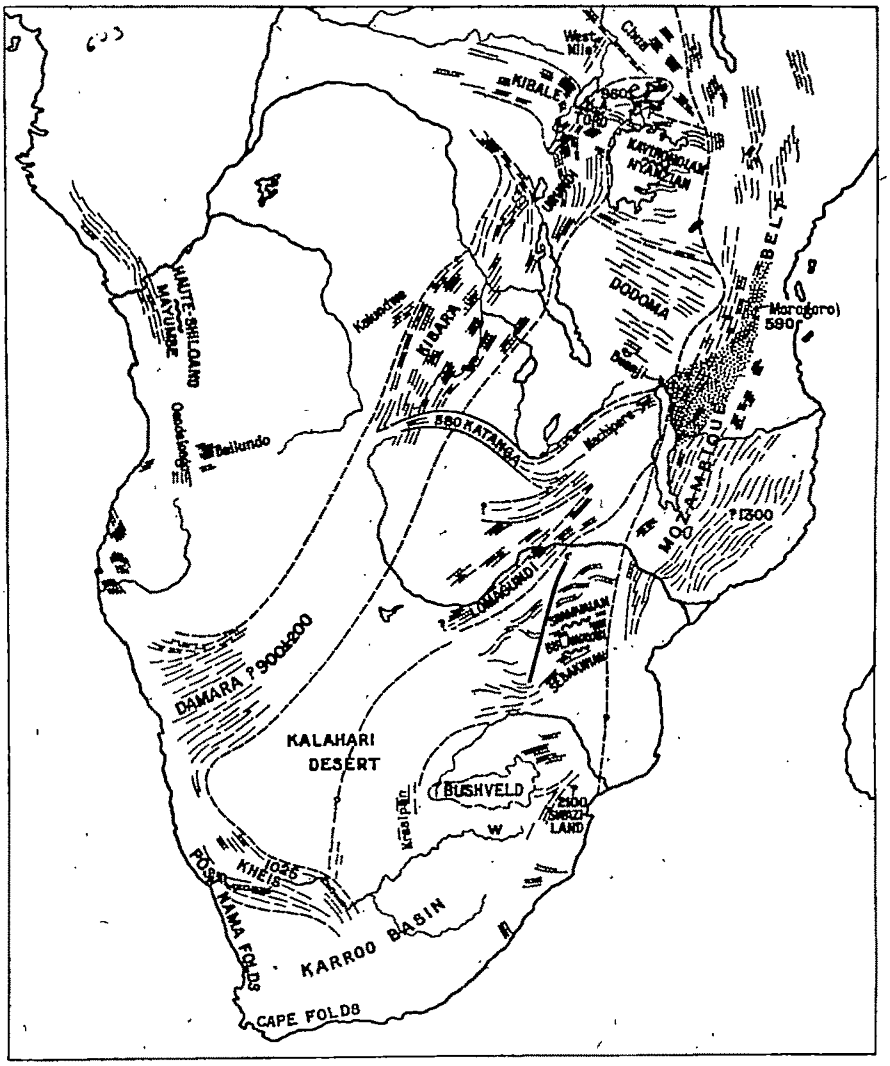

Figure 2. Provisional map of Pre-Cambrian orogenic belts in South and Central Africa. The figures represent the "ages" of radioactive minerals in millions of years. Only those from Katanga, Morogoro and Gordonia (Kheis) have been controlled by isotopic analysis of lead. The others remain "crude." K.-A. = Karagwe-Ankolean; W = Witwatersrand. The dotted area represents a supposed extension of the Katanga and Lomagundi belts, linking the latter with the late Pre-Cambrian pegmatites of Morogoro.

radioactive mineral which might serve as an age-index has been analysed, a euxenite from Uganda. The data presented in table 5 show that the apparent age is 920 ~ 995 m.y.

TABLE 5

Euxenite from Uganda

	Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent age in m.y.
E.	1.54	8.42	4.85	.125	.75	995
F.	1.43	9.30	2.95	.117	.76	920

E. Original sample from vein in Mubende granite, near Kagadi, West Buganda. *Analyst:* W. H. Bennett (both analyses communicated by the Imperial Institute, London).

F. Purified material separated from the same sample as E. *Analyst:* W. H. Bennett.

In a paper presented to the London Session of the International Geological Congress in 1948 I adopted the "age" of the purified euxenite, 920 m.y., as likely to be more reliable than that of the original sample, 995 m.y., and suggested a correlation with the Gordonia uraninite. The further investigation of the latter, as recorded in this paper, has shown, however, that the original sample B gives a much more nearly correct "age" than the fresh-looking material separated from it. In the case of the euxenite there is consequently no longer any adequate reason for giving preference to the lower age. The crude ages, uncorrected by isotopic analysis, are as follows:

Uganda euxenite	920 — 995 m.y.
Gordonia uraninite	875 — 1125 m.y.

The correlation is only very rough, but, pending further investigation of radioactive minerals from the Kibara—K.-A. belt, it may be tentatively adopted as a working hypothesis.

As indicated in figure 2 correlation of the Kibara—K.-A. belt with the Kheis belt suggests that the Damara belt of S.W. Africa may also be part of the same orogenic belt. Preliminary age estimates of the post-Damara pegmatites by the strontium-rubidium method have been made by Ahrens (1948; 1949). His latest statement of the results is summarised in table 6, from which it would appear that the crude age of the pegmatite minerals is about 900 ± 200 m.y. In his 1948 paper Ahrens adopted an earlier value for the disintegration constant for rubidium and arrived at "ages" about 100 m.y.

higher than those now given: the average "age" and range being then about 1000 ± 200 m.y.

TABLE 6

Age Estimates of Post-Damara Pegmatite-Minerals (S.W. Africa) by the Sr/Rb Method (Ahrens, 1949)

Minerals and Localities	*No. of Determinations*	*Apparent Age in m.y.*
Lepidolite, Okongava Ost 72, Karabib	(6)	750
" Karabib	(3)	700
" Albrecht's Höhe, Karabib	(4)	850
" Warmbad	(2)	950
" Omaruru	(4)	1150
Lithium-muscovite, Usakos	(3)	1050
Weighted Average	(22)	905

It is difficult at present to interpret these results with confidence and it will remain so until isotopic determinations of Sr^{87} have been completed. One might reasonably suppose that "strontium ages" would tend to be too high because of the possible presence of original Sr, not allowed for in the calculations. If this supposition covered all the possibilities of error, the lower "strontium ages" in table 6 would be the more reliable and the Damara belt could not then be correlated with the Kheis belt, but would probably be intermediate in geological age between the Katanga and Kheis belts. If this were really so, it would have far-reaching consequences which are too complex for brief discussion here. However, there seems at present to be no compelling reason for giving preference to the lower ages. Ahrens himself has pointed out that the crude ages obtained from pollucite are always less than the expected age, possibly because of the presence of caesium. The cause of this known discrepancy—whatever it may be—might also be responsible for the low "ages" of some of the samples of lepidolite investigated.

Another example of a known discrepancy, which admittedly is exceptional, is provided by the conflicting data for minerals from the well known Ingersoll pegmatite in the Black Hills of South Dakota. Uraninite, analysed by Davis (1926) has an apparent age of 1880 m.y. Judging by the good quality of the analysed material and the excellence of the analysis, I find it difficult to believe that this result could be more than 100 m.y. in error. Yet Ahrens obtains crude ages of 800 and 900

m.y. for two specimens of lepidolite from the same pegmatite. Another Black Hills lepidolite of which the exact locality is not known, gives an "age" of 1500 m.y. To clear up the present doubt as to the age of the Ingersoll minerals and to locate the error responsible for that doubt, it is obviously highly desirable that the isotopic constitution of the lead from the uraninite analysed by Davis should be determined as soon as possible.

Meanwhile it would be premature to assume that the age of the post-Damara lepidolites lies in the range 700-900 m.y. rather than in the range 900-1100 m.y. Nevertheless, while doubt remains, the suggested correlation of Damara with Kheis on the one hand and with Karagwe-Ankolean on the other can only be regarded as provisional.

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NEW EVIDENCE ON THE CAMBRIAN CONTACT AT HOPPIN HILL, NORTH ATTLEBORO, MASSACHUSETTS

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ABSTRACT. A re-examination of Hoppin Hill, North Attleboro, Massachusetts, yielded an actual exposure of the sedimentary contact between the white, basal quartzite of the lower Cambrian formation and the coarse, pink granite of the Dedham granodiorite, thus substantiating the interpretation put forth by M. P. Billings in 1929. So far as can be determined, no exposure of the contact itself has been observed previously.

INTRODUCTION

THE writer became concerned with the problem of the age of the Dedham granodiorite when mapping the Medfield and Holliston, Massachusetts, quadrangles for a Ph.D. thesis. These quadrangles have no fossiliferous rocks and yield only the evidence that the Dedham is pre-Mattapan volcanics (Devonion?) and post-Marlboro formation (probably pre-Cambrian). The writer is very grateful to Professor M. P. Billings for helpful discussion of the problem and for making available a student field report of the Hoppin Hill area.

Hoppin Hill, in North Attleboro, eleven miles south of the Medfield quadrangle, is a granite knob with fossiliferous Lower Cambrian slates cropping out on the east side and it is completely surrounded by Carboniferous sediments of the Narragansett Basin. For fifty years this locality, the most important locality in the dating of the Dedham granodiorite, has been a source of geological argument.

PREVIOUS WORK

Shaler, Woodworth and Foerste (1899, plate 27) gave a sketch map of the east side of the hill and described in detail the fossil localities. They were uncertain about the age relations because the actual contacts were not exposed. They state (p. 390) that "the Cambrian strata apparently follow the general trend of the eastern margin of the granite hill", and (p. 391) that "the temptation is very strong to consider the quartzite and the associated green shales as forming the lowest beds of the series." However, under general features (p. 8) they state "on top of this formation (Lower Cambrian) and

the granites which have broken through it, come the Carboniferous beds."

C. H. Warren and S. Powers (1914, pp. 459-460) interpreted the structure as an intrusive contact of granite against the lower Cambrian slates, thus indicating a post-Cambrian age of the granite.

B. K. Emerson (1917, p. 37) accepted Warren and Powers' conclusion that the granite is younger than the Hoppin slate. He stated that "the base of the Cambrian strata is not exposed in the district and their thickness is unknown, but is probably not less than 600 feet."

M. P. Billings (1929, p. 103) assigned the Dedham-Salem group to the pre-Cambrian because — "at Hoppin Hill, North Attleboro, the fossiliferous Lower Cambrian slates rest unconformably on eroded granodiorite. A basal quartzite about ten feet thick intervenes between the slates and the granodiorite."

C. R. Williams, as a student under Dr. Kirk Bryan and Dr. Marland Billings at Harvard University, made a field study of the Hoppin Hill area when the reservoir was particularly low in 1930. He measured the thickness of the Cambrian strata as 340 feet, including 15 feet of white quartzite at the base (1931, manuscript report loaned by Professor Billings).

L. La Forge (1932, p. 22) stated that "the Dedham granodiorite is almost surely younger than the Cambrian rocks of the region, and the gabbro or norite of Nahant, which is here included in the group, is certainly post-Cambrian." He gave the age as probably early Paleozoic.

PRESENT WORK

In February 1949, when the writer visited Hoppin Hill, the reservoir covered much of the fossiliferous red slate and limestone north of Hoppin Hill Avenue, and reached directly

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PLATE 1

Fig. 1. Steep ledge of coarse granite at right; white quartzite in left center resting against the granite.

Fig. 2. Close view down into excavation along the contact. Granite on right and quartzite dipping away steeply to left. Strike N87°E, dip 78°SE.

Fig. 3. Steep ledge of granite on left, quartzite in center foreground. Topographic shelf, developed on the quartzite, shows in right half of picture.

(3 photos from locality 1, marked in Fig. 1)

FIGURE 1

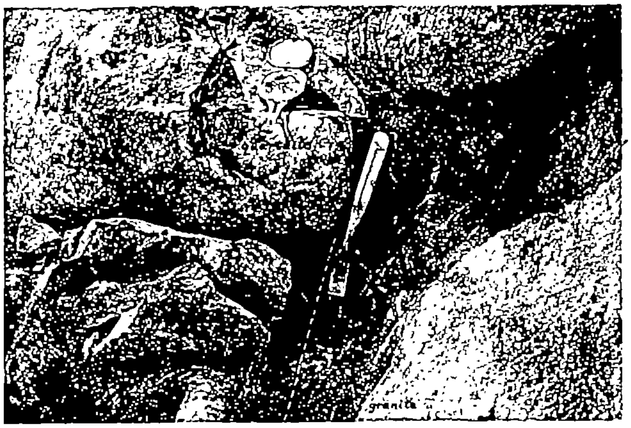

FIGURE 2

FIGURE 3

to the granite on the steep lower east side of the hill. At least two outcrops of the fossiliferous strata can still be seen north of the reservoir, one on the south side of the railroad and one in the meadow close to the north side of the railroad embankment (marked f in fig. 1).

The writer turned attention from the fossiliferous strata to the basal quartzite noted by Billings (1929, p. 103). A greenish white quartzite can be seen at the water's edge on the west side of the reservoir about 50 yards south of Hoppin Hill Avenue (fig. 1, locality 2). At the south end of the hill is an elongate, rocky knoll of elevation 250 feet (fig. 1, locality 1). At approximately the 230 foot contour on the southeast side of the knoll is a shelf or shoulder, 10 to 25 feet wide and about 100 yards long. The shelf has a long continuous outcrop of hard, white quartzite dipping away from the granite that forms the top of the knoll and dipping toward the red shale. The granite is coarse-grained, pink and white, with milky quartz standing a quarter inch above the pitted pink feldspar on the weathered surface.

At one spot the quartzite and granite were only one foot apart and in several places less than ten feet apart. Excavating a few inches of soil at the spot where the granite and quartzite were closest revealed the actual contact in somewhat crumbly rock at the bottom of a trench ten inches deep and four inches wide at the bottom. The granite maintains its coarse grain (several millimeters) directly to the contact. At the contact the feldspar is kaolinized and bleached to a light buff color and a little chlorite and epidote are present. In the bottom few inches of quartzite are some grains as large as two millimeters, whereas higher up the grains are mostly less than one half millimeter. No indication of shearing or slipping occurs on the contact. Thus, the sedimentary contact of basal white quartzite against the granite is definitely proved and the possibility of a fault contact or intrusive contact is clearly eliminated. The strike and dip of the contact is N37°E, 78°SE. Plate 1, figs. 1, 2 and 3, show the ledge of granite, the small excavation along the contact, and the quartzite resting unconformably on the granite (fig. 1, locality 1). To the writer there is no longer any doubt of the pre-Cambrian age of this granite.

To try to reconcile Warren and Powers' (1914, pp. 459-

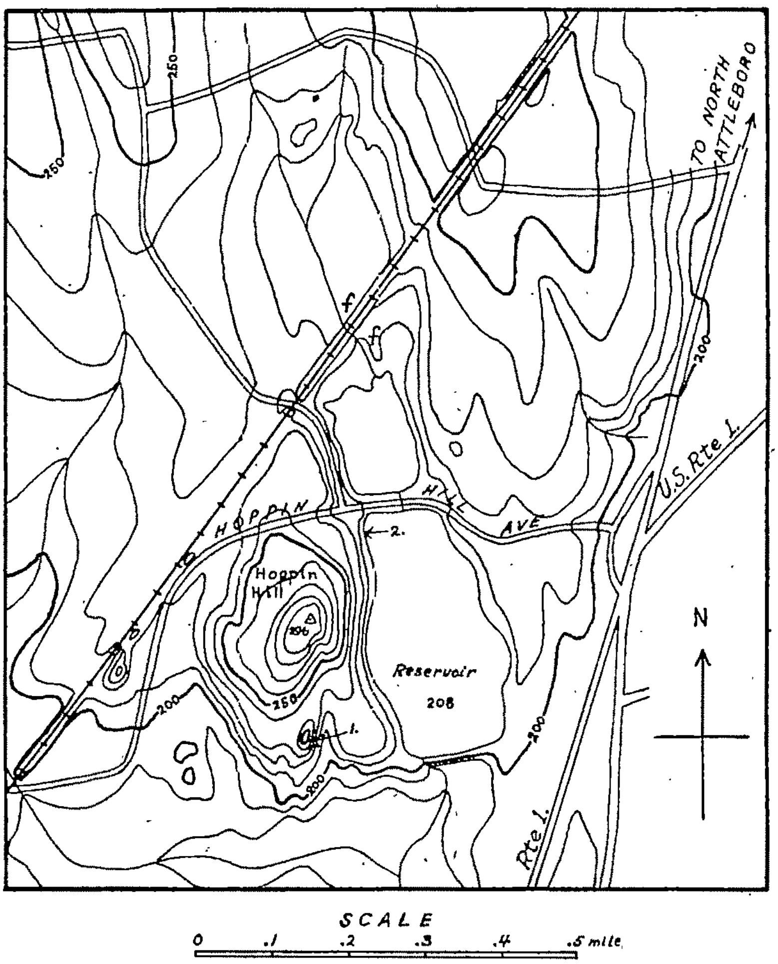

Fig. 1. Map of Hoppin Hill, North Attleboro, Massachusetts, enlarged from U. S. G. S. Attleboro quadrangle. Locality 1 marks the exposure of the sedimentary contact, N37°E, 78°SE. Locality 2 has quartzite dipping eastward. Fossiliferous Cambrian outcrops are indicated by f.

460) opposing view, it may be noted that they described only the outcrops north of Hoppin Hill Avenue. Those outcrops consist chiefly of red shaly limestones, so susceptible to deformation that slaty cleavage is more prominent in them than bedding. The few outcrops still above the reservoir do

not reveal enough indication of bedding to warrant the statement that they strike toward and dip into the granite.

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A DEEP FATHOGRAM ACROSS THE NORTH ATLANTIC OCEAN

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ABSTRACT. Continuous automatically recorded echo-soundings from depths as great as 3000 fathoms were obtained during a recent crossing of the North Atlantic Ocean. These revealed some of the characteristics of the deep-sea floor in greater detail than is permitted by ordinary echo-sounding tracks in deep water. Study of the tape record, or fathogram, shows something of the physiography of the area, the processes of sedimentation, and the geological history.

INTRODUCTION

A CROSSING of the North Atlantic Ocean between Norfolk, Va., and Gibraltar during the period July 7-19, 1948, by the *U.S.S. Siboney* provided an opportunity for making nearly continuous fathograms of the ocean floor. This vessel, an aircraft carrier, carried an echo-sounder capable of recording at all depths encountered. Through the co-operation of the commanding officer and the navigator, the writer was able to observe the sounding operations.

The equipment operated at 18 kilocycles per second and was built to record to a depth of 2000 fathoms. Shortly before the trip, however, it was modified by a simple adjustment so that soundings deeper than 2000 fathoms could be made. Use of the regular depth scale selector knob then permitted recordings to be made between 0 and 100, 100 and 200, 0 and 2000, or 2000 and 4000 fathoms. The appearance of the record on the various scales is presented in accompanying photographs of sections of the recording.

Previous data in the area have been obtained by many ships which took spot-soundings, usually at equal intervals of 4 hours. Some fathograms have been made, but only where the bottom is shallower than 2000 fathoms. The soundings shown on the navigational charts are from many such sources, and because of their composite nature they may show great irregularities where none exist, while in other places they may give an incorrect impression of flatness because of the wide spacing between some soundings. Such errors may not be serious in use of the charts for general navigation, but it does restrict

the making of geological deductions. A continuous profile made by a single ship is more satisfactory as a geological guide. The best known deep-sea floor profiles are those made in the South Atlantic Ocean by the German ship *Meteor* (Stocks and Wüst, 1935), from which spot-soundings were obtained at about 4-mile intervals.

RESULTS

A summary profile, shown on figure 1, is based on soundings read directly from the fathograms at 15-minute intervals (2½ to 4½ miles, depending on ship speed). Some intermediate additional soundings were included to show peaks and valleys. No correction was made for the difference between the actual sound velocity and the calibration velocity of 4800 feet per second, nor for the keel depth position of the hydrophone. Thus, the fathograms show depths 5 fathoms too shoal in shallow water with the error increasing to as much as 80 fathoms in 2500 fathom depths. While the general profile does not present much detail, it is useful in indicating the main physiographic divisions of the region and in serving as a position index for the selected portions of the fathogram given in figure 2. Note that the general profile has a vertical exaggeration of 75, in contrast to the fathograms which have a vertical scale only 5 to 8 times the horizontal scale, depending on the ship's speed.

The first major physiographic feature encountered was the continental shelf. Off Norfolk it is so gently sloping that depths greater than 20 fathoms are reached only beyond 25 miles from shore. In this shallow portion there are numerous irregularities, possibly large sand waves. The shelf is somewhat steeper between 30 and 45 fathoms, but the main break in slope is at 53 fathoms, the edge of the shelf in this area.

The continental slope section of the profile is steepest between 150 and 700 fathoms, but continues fairly steep to 1500 fathoms. Beyond that depth, a flatter area, 250 miles wide, may be due in part to the ship's course being nearly parallel to the slope and in part to the possible existence of a deep terrace. At a point 200 miles southeast of New York City, the profile shows a deep "V" extending to a depth of 1850 fathoms, 270 fathoms below the "terrace" level of 1580 fathoms. This is evidently a cross-section of the Hudson Submarine Canyon

which is well beyond the outer limit of the detailed surveys reported by Veatch and Smith (1939). A short length of the fathograms (fig. 2-A) shows the canyon and a nearly flat area 70 fathoms below the "terrace" which may be the floor of another canyon. Seaward of the deep "terrace," the continental slope again steepens down to about 2300 fathoms, where it merges into the deep-sea floor.

At a point 450 miles from the start of the profile is a deep fairly flat area 700 miles wide which is known as the North America Basin. The floor begins at 2300 fathoms at the west side and gradually deepens to between 2640 and 2690 fathoms across almost the whole eastward half. South of this profile, west of Bermuda, the basin is as much as 700 fathoms deeper. A number of broad, low undulations of the fathogram (fig. 2-B) may be due to local irregularities in sedimentation or in compaction rates, but others like the unnamed peak found at the 520-mile point may be of volcanic or fault origin. The east side of the peak has a slope of 20°, although it appears to be steeper on both the profile and the fathograms. Some soundings on charts of this basin are as much as 250 fathoms deeper than those obtained by the echo-sounder at the same positions. This difference is interpreted as due to the fact that the older charted soundings were made by wire; such soundings in deep water are often too great because of drifting of the ship before the lead weight reaches bottom.

On its northeastern side the North America Basin is limited by an extension of the Grand Banks. The fathogram indicates two main shallow areas of 1480 and 1390-fathom depths (figs. 2-C, 2-D). A change in instrument setting from the 2000-4000 to the 0-2000 fathom scale is shown by figure 2-C. The steepest side slopes of the high areas are only about 5°. On the east side of the extension is a terrace about 1750 fathoms deep and 30 miles wide.

Beyond the Grand Banks is the Newfoundland Basin, about 650 miles wide here. Its depth along the profile increases from about 2200 fathoms on the west side down to 2500 to 2600 fathoms 100 to 200 miles eastward. Figure 2-E shows a portion of the deeper part crossed by the ship. Near the middle of the basin several broad, flattish hills rise above the surrounding area (fig. 2-F). There are more and higher hills toward

the eastward margin of the basin. Figure 2-G shows an area where the hills are so close together that the bases of many adjoin, but in general the floors between hills are flat and at about the same depth as the middle of the basin. It is in this area that a depth of 2650 fathoms was recorded, the greatest depth in the basin on this crossing. Depths about 100 fathoms deeper than this are reported somewhat south of the profile.

The ship crossed the Mid-Atlantic Ridge just north of the Azores, where it has a width of 500 miles, 350 of which are shallower than 1100 fathoms. Numerous separate hills are present, and several are shallower than 600 fathoms (fig. 2-H). The Azores, of course, are similar hills which reach well above sea level. In addition to much irregular topography the ridge also contains some wide, flat terrace areas, one of which (fig. 2-I) is more than 50 miles wide and is characterized by depths between 800 and 900 fathoms.

The easternmost deep area crossed, known as the Iberia Basin, markedly differs from the other basins in the great irregularity of its floor. It contains a great series of low hills plus a broad zone including Josephine and Gettysburg Banks which rise from 2500 fathoms to a charted depth of only 23 fathoms. A fairly flat shoulder of Josephine Bank is shown by figure 2-L. Soundings of the top of Gettysburg Bank were taken from the chart because the *Siboney's* echo-sounder was inoperative at the time the bank was crossed. The Iberia Basin contains the greatest depth of the entire profile, 3040 fathoms (fig. 2-J), which also is the maximum depth charted for any part of that basin. Between some of the hills of the basin floor are flat areas usually not more than 20 miles wide. Part of one is included in figure 2-K. The only very extensive flat area is at the base of the continental slope where for a distance of 50 miles the bottom lies between 2500 and 2550 fathoms.

The continental slope, which forms the eastern limit of the Iberia Basin, has a fairly irregular slope of about 2°. It grades into the continental shelf at 60 fathoms. The continental shelf in this area forms a narrow sill, or divide, separating the basin of the Atlantic Ocean from that of the Mediterranean Sea. This divide is 85 miles west of the narrowest part of the strait of Gibraltar. The deeper water within the strait (fig. 1)

may be partly the result of erosion by an undercurrent of dense, salty water leaving the Mediterranean Sea.

In addition to indicating bottom topography the fathograms show the general presence of a sound-reflecting layer in the water. This layer was consistently present during the day and absent at night. When present, it resulted in strong reverberation usually between depths of 220 and 360 fathoms, causing a belt of echoes just below the out-going signal on the fathogram (figs. 2-A, 2-C, 2-H, and 2-L). Besides being present in the Atlantic Ocean, the layer was found in the Mediterranean Sea, the Red Sea, and the Indian Ocean. In general characteristics it is exactly similar to a layer which previously had been reported from the northern and southern parts of the Pacific Ocean (Dietz, 1948). It is generally believed that the sound passing through the water is partially reflected by myriads of organisms, which swim downward to escape bright sunlight during the day and upward to feed on phyto-plankton during the night. Because this layer is such a good sound-reflector, echoes from it may sometimes be misinterpreted as indicating bottom at that depth.

GEOLOGICAL CONCLUSIONS

Two of the three major basins crossed by the ship are characterized by floors which mark the top of a sediment fill and which are generally flat except for somewhat broad, low undulations of the order of 10 fathoms in a distance of a few miles. These irregularities may be the result of slightly unequal rates of sedimentation or of compaction. The width and the flatness of the basin floors is probably an index of the relative rates of sedimentation and of the duration of undisturbed sediment accumulation. It is noteworthy that the North America Basin is widest and flattest and, therefore, presumably has been receiving sediments faster or for longer time without interruption by strong vulcanism or faulting. In contrast to the low undulations are sharp peaks which rise abruptly from the flat basin floors to heights of more than half a mile. These peaks are rare in the North America Basin, and present only at the east side of the Newfoundland Basin, but they make up almost the entire cross-section of the Iberia

Basin. Their side slopes are of the order of 10° in steepness. Very likely most of them are the result of submarine vulcanism or faulting, a conclusion which is supported by the fact that they are most abundant on and near the Mid-Atlantic Ridge, one of the principal belts of earthquakes and vulcanism.

The high, shallow areas crossed by the fathogram are also of considerable interest. The most outstanding of these is the Mid-Atlantic Ridge which just north of the Azores is a broad plateau mostly between 800 and 1100 fathoms, above which many hills rise to 600 fathoms or shallower. From the irregular character of the fathograms there, it appears that sediments in most of the area are present only in a very thin layer. Possibly sediment accumulation is the cause of the smooth, flat portions of the ridge, but because some of these areas are marginal and deeper than the peaks, they more probably are due to wave erosion during some past time of lowered sea level. These flat areas may have the same uncertain origin as the abundant flat-topped sea-mounts reported at depths of 700 to 800 fathoms in the Pacific Ocean (Hess, 1946). Much additional data on the depth and composition of the terraces south of the Azores is being obtained by Ewing and his associates (Tolstoy and Ewing, 1948).

NAVIGATION

Fathograms and profiles made manually from visual echo-soundings have long been used as navigational aids in relatively shallow water of well-sounded coastal areas. By recording and plotting soundings for a few miles, a cross-section can be drawn on a scale corresponding to the chart. Depths along this cross-section usually will be found to fit the contoured navigational chart only at one place. Such unique features as the Hudson Canyon and the unnamed nearby peak allow extension of such methods well out to sea in some regions. Similarly, the recording echo-sounder may be helpful in navigation in midocean, even where surveys are poor, provided that prominent features like the Mid-Atlantic Ridge are present. It is possible also that in time a sufficiently accurate survey of the very irregular floors of basins bordering the Mid-Atlantic Ridge may permit the construction of detailed charts of these

areas. Such charts would be very useful in navigation as well as constituting a source of new geological information.

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RADIUM CONTENT OF ULTRAMAFIC IGNEOUS ROCKS: III. METEORITES

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ABSTRACT. Measurements of the radium content of some pallasites and iron meteorites have been made by a refinement of the vacuum fusion technique. In general, the radium content of the meteorites investigated is lower than that of terrestrial ultramafic rocks and minerals. Radium contents are also given for one stony meteorite and one amphoterite.

INTRODUCTION

IN Part I of this series of papers dealing with the radium content of certain ultramafic igneous rocks (Davis, 1947), the radium content of a pallasite was measured in order to obtain a value that might be representative of an ultramafic rock of more deep-seated origin than those available at the surface of the earth. The values obtained were so much lower than previously published results (Joly, 1909; Quirke and Finkelstein, 1917; Paneth and Koeck, 1931; Evans, 1938; Schumb, Evans, and Hastings, 1939) that it was deemed worthwhile to measure a few more meteorites in order to confirm the order of magnitude of the results and to verify the measured difference between the olivine and the metal portions of pallasites. During the course of the investigation, more recent data became available in the work of Paneth and his co-workers (Arrol, Jacobi, and Paneth, 1942), whose results on six iron meteorites indicated extremely low radium contents compared to Paneth's earlier results.

The same apparatus, precautions, and refinements in technique employed in the first paper of this series (Davis, 1947) were applied in making the present measurements. A few modifications were necessary because of the nature of the materials studied.

SAMPLE PREPARATION

All specimens were obtained through the courtesy of E. P. Henderson, Curator of Mineralogy and Petrology of the United States National Museum. The samples were cut from larger pieces at the Museum with an abrasive-fed band saw which was cleaned as well as possible before use to remove contaminating material. Distilled water and fresh abrasive

were used. A sample of the carborundum was withdrawn and tested later; it was found to have no contaminating effect.

In the Laboratory samples were cut to appropriate size with a rubber-bonded carborundum cut-off wheel, cleaned and trimmed with a dental grinding tool, washed with distilled water, dried between filter papers, and stored in a dessicator until ready for final treatment. Olivine samples were broken out of the centers of freshly-cut, thin slabs of pallasite and cleaned magnetically. Metal samples were cleaned by three treatments with redistilled hydrochloric acid of measured negligible activity, with alternate and final rinsing in specially distilled water that had previously been shown to be inactive.

EXPERIMENTAL PROCEDURE

All measurements on stony meteorites, amphoterites, and olivine from pallasites were made by direct fusion in the graphite troughs which serve as heating elements in the vacuum fusion furnace. Some of the iron meteorite samples were also fused directly, but the molten iron attacked the graphite container to a considerable extent, and high values of the radium content obtained in early determinations were suspected of being due to exposure by this attack of a portion of the graphite that had not been sufficiently out-gassed in the preliminary and background heating. Attempts to make a nonradioactive liner for the graphite trough capable of being heated and reheated according to the schedule of operation, and, at the same time, being relatively unreactive toward carbon and iron in a vacuum at temperatures in the neighborhood of 2000°C finally culminated in the use of a boat of periclase. Electric furnace periclase in grains sized between 20 and 150 mesh was mixed with an absolute minimum of high temperature cement, RA 518, moistened, and formed into a shallow boat in a graphite trough. After oven drying at 120°C the boat and trough were placed in the vacuum fusion furnace and heated to more than 2000°C at least three times. This treatment sintered the refractory material and made it possible to transfer the boat to a preheated trough, the original one having been pitted in the sintering process. Most of the high temperature cement distilled to the walls

and supports of the furnace during the preliminary heatings. The resulting boat was porous, pure white, and showed no reaction on subsequent heating with either the graphite or iron. Some vapor transfer of MgO was evident by the formation of colorless needles of periclase at "cool" parts of the boat. Similar effects were noticed when a boat was milled out of a single crystal of periclase, the surface becoming etched and crystal planes being developed, and sharp corners being rounded.

The boats formed from periclase and high temperature cement gave somewhat higher backgrounds than the graphite troughs alone, but this may have been due to the longer period of heating at the higher temperatures.

RADIUM CONTENT OF METEORITES

The results of the radium determinations on specimens of twelve meteorites are given in table 1. The radium content is expressed in the usual units, 10^{-12} gram of radium per gram of sample, and is followed by the probable error of the result, r_3, as discussed in Part I of this series (Davis, 1947). In the last column the radium contents have been expressed as uranium in units of 10^{-8} gram per gram.

Radioactive contamination of these specimens by handling and preparation can hardly have occurred, except in the case of one meteorite, since the results are so low. The single case of suspected contamination is P-406, Antofagasta, where the olivine gave an unexpectedly high value for the initial determination of 0.018 units of radium. Another determination was made using olivine fragments which had been rinsed three times in "radioactively inactive" hydrochloric acid. The result given in the table was obtained. Further treatment probably would have reduced the radium value, but the "inactive" acid soon would have become a contaminant as it would be impossible to remove all the acid from the shattered crystals. The physical appearance of this specimen indicated the possibility of contamination during its terrestrial existence, the metal showing considerable oxidation and the olivine having cloudy alteration films along cracks in the badly shattered crystals. The treatment of the metal portions was evidently effective in removing the contaminated surface.

TABLE 1
Radium Content of Meteorites

No.	USNM No.	Name		Ra × 10^{-12} g./g.	U × 10^{-6}
		Medium Octahedrites			
P-371	645	Mesa Verde Park, Colo.		<.0004	< .12
P-408	986	Carthage, Tenn.		.0015 ± .0009	.44
P-409	663	Thunda, Queensland		.0008 ± .0007	.24
		Octahedrites			
P-372	1413	Edmonton, Ky.		<.0009	< .26
P-375	846	Glorieta, N. M.		.0017 ± .0004	.5
		Hexahedrites			
P-373	1307	Sierra Gorda, Chile		.0017 ± .0006	.5
P-374	1379	Cedartown, Ga.		.0008 ± .0004	.24
		Average		.0011	.33
		Pallasites			
P-376	1333	Salta, Argentina	(metal)	.0065 ± .0010	1.9
			(olivine)	<.0004	< .12
P-406	1207	Antofagasta, Chile	(metal)	.0035 ± .0006	1.0
			(olivine)	<.005*	<1.5*
P-407	823	Brenham, Kan.	(metal)	.0027 ± .0008	.79
			(olivine)	<.0003	< .09
		Metal average ..		.0042	1.23
		Amphoterite (Hypersthene-Olivine-Achondrite)			
P-410	1235	Shaw, Colo.		.0164 ± .0007	4.8
		Stone			
P-411	604	Cumberland Falls, Ky.		.0034 ± .0013	1.0

*contaminated.

The results given in the table indicate that the radium content of meteorites is as low as or lower than most ultramafic rocks. The values for iron meteorites obtained in this investigation agree in magnitude with those recently presented by Arrol, Jacobi, and Paneth (1942) and justify the rejection of values from earlier measurements. Samples of specimens of the same meteorite were analyzed in two cases and the results are in surprising agreement for independent determinations of such small amounts of radium.

		This paper	A,J,P
P-408	Carthage	.0015 ± .0009	.0017
P-409	Thunda	.0008 ± .0007	.0028

The values in table 1 tend to be slightly lower than those referred to above:

Average of six iron meteorites (A,J,P)	.0025
Average of seven irons (this paper)	.0011

but the difference can hardly be considered significant when based on so few determinations.

The determinations of radium in pallasites tend to confirm the single result, obtained in Part I of this series of papers, that the metal portion contains more radium than the silicate. The radium content of Salta, P-376, was redetermined and the values remain essentially unchanged. It also seems probable that the metal portions of pallasites contain more radium than do the iron meteorites, while the olivine portions may contain less.

While this paper was in proof, a note from Dr. Henderson was received in which he indicates that the Salta and Antofagasta meteorites may be related. His recently completed analyses of the olivines from the two pallasites are almost identical. Thus, in at least two cases, the pallasitic olivine contains less radium than does the metal—a most unexpected result, and one which might invite further investigation.

The results of these radium determinations on meteorites as well as those on ultramafic rocks given in Part I have been used by Urry (1949) in presenting a theory of the thermal history of the earth. If the dunites and meteorites are considered to represent the monomineralic mantle and the core of an earth model, their extremely low radium contents indicate that no embarassingly large amount of heat is being generated by radioactive disintegration.

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ACCESSORY SULFIDES IN NORTH CAROLINA PEGMATITES

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ABSTRACT. Pegmatites of the Franklin-Sylva and several other pegmatite districts in North Carolina are characterized by a late hydrothermal phase, in which sulfides, chiefly pyrrhotite and pyrite, formed replacements and veins in older pegmatite minerals and in gneissic wall rocks. The sulfides were among the very last minerals to crystallize. Sulfides in feldspar almost invariably are surrounded by halos of green color due to sericite and probably a fine-grained clay mineral. Polished section studies reveal that the pyrrhotite is very coarse-grained and that some has a lamellar exsolution structure. Pyrite, some of it slightly anisotropic, and chalcopyrite formed after pyrrhotite. An unusual associate in a few deposits is diopside-hedenbergite. The most typical sequence in the sulfides is pyrrhotite, pyrite, chalcopyrite, and marcasite.

Introduction

MANY pegmatites of several Piedmont and Blue Ridge districts in North Carolina contain small amounts of accessory sulfide minerals. The purpose of this study is to describe the mineralogy and paragenesis of some of these occurrences. The writer became familiar with the geology of the mica-bearing pegmatites during the period January, 1944, to September, 1945, as a member of the U. S. Geological Survey. Material for this investigation was collected in the spring of 1948. This study of pegmatitic sulfides is part one of a general investigation of opaque pegmatite minerals in polished sections initiated by the writer under a generous grant from the Faculty Research Fund of the Rackman Graduate School of the University of Michigan. The writer is indebted to Professor K. K. Landes of the Department of Geology, University of Michigan, for a critical review of the manuscript.

The general geology of the southeastern pegmatite districts has been sketched (Griffitts, Heinrich, *et al.*, 1946) and a detailed account of the various districts is in preparation.[1] Most of the descriptions in this report are of occurrences in the Franklin-Sylva district in the southwest corner of the state, which has been studied by Sterrett (1923), Sharp (1942), and by Olson and others (1946). Several descriptions of occurrences in the Shelby district in Cleveland County, which

[1] Mica Deposits of the Southeastern States, U. S. Geol. Survey Bull., in press, by members of the staff, U. S. Geol. Survey.

is in the Piedmont near the South Carolina line, also are included.

General Geology

The Franklin-Sylva mica pegmatite district is in Haywood, Macon, Jackson, Transylvania, and Clay counties, North Carolina, and extends southward into Rabun County, Georgia. From 1920-1940 it yielded 20% of the North Carolina mica production. It is 60 miles long in a northeast direction and 35 miles in maximum width. Three main rock types are present: The Carolina or micaceous gneiss, the Roan or hornblendic gneiss, and the intrusive Whiteside granodiorite-quartz diorite of probable Carboniferous age, to which the pegmatites are related. The pegmatites, which occur chiefly in gneiss on the northwest side of the Whiteside intrusive, are quartz monzonitic to granodioritic in composition. Some 700 deposits have been mined or prospected. The main pegmatitic minerals are oligoclase, (Ab 70-86), quartz, microcline, and muscovite. Common accessories, in addition to the sulfides, are biotite, garnet, apatite, sericite, albite, and magnetite (in mica). Other rarer minerals and the number of their recorded occurrences are beryl (4), black tourmaline (8), allanite (4), diopside-hedenbergite (3), samarskite (2),[2] kyanite (2), hornblende (2), sillimanite (2), and one recorded occurrence each of ankerite, graphite, gahnite, pink tourmaline, zircon, epidote, autunite, torbernite, uranophane, staurolite, and ilmenite. Pyrrhotite (31 occurrences) is by far the most abundant of the sulfides and is followed by pyrite (15); chalcopyrite (7) is not common, and bornite (1) is rare.

A mineralogical comparison of several districts in the southeast shows that each has its own characteristic suite of accessory minerals. In the Alabama district and the Thomaston-Barnesville district of Georgia pyrite and pyrrhotite appear

[2] A polished section of samarskite from the Sheep Cliff deposit near Cashiers in Jackson County shows that the mineral consists of two substances. The more abundant is somewhat lighter gray in color, isotropic, very hard, with dark reddish brown internal reflection, and is negative to all the standard etch reagents, including aqua regia. The subordinate, darker gray material occurs as ragged inclusions and has similar properties but shows a stronger yellow brown internal reflection. An autoradiograph, made with 100 hours exposure on Eastman Alpha particle plates, reveals some variation in radioactivity of the sample, but this variation does not correlate with the distribution of the two substances.

to be rare, even in the unweathered parts of deposits. Only two occurrences of pyrite are recorded in the Alabama district. However, black tourmaline, which is exceedingly scarce in the Franklin-Sylva district, is common in both the Alabama and Thomaston-Barnesville district, and in the latter, beryl occurs in many of the deposits. The pegmatites of the Shelby district in North Carolina contain more microcline than those of the Franklin-Sylva district and also have accessory calcite, zeolites, beryl, pyrite, and pyrrhotite.

Accessory pegmatite minerals in the Spruce Pine district include biotite, garnet, apatite, magnetite, ilmenite, allanite, epidote, thulite, zoisite, calcite, beryl (including emerald), columbite, monazite, cyrtolite, samarskite, uraninite, clarkeite, rogersite, gummite, autunite, uranophane, kyanite, gahnite, spodumene, and hyalite (Olson, 1944; Sterrett, 1923). Sphalerite has been abundant at the McKinney mine (Ross, 1937), associated with minor quantities of chalcopyrite, pyrrhotite, pyrite, galena, covellite, and scheelite. This accessory suite differs from that of the Franklin-Sylva district by a much greater variety, by a wider distribution, by the occurrence of calcium silicates, by greater abundance of uranium minerals, and by a scarcity of iron sulfides.

Sulfides

Franklin-Sylva District

Sulfides favor three loci in Franklin-Sylva pegmatite deposits: the quartz core, especially its margins; the outermost part of the pegmatite, either border zone or part of the wall zone; and the wall rock near the pegmatite contacts. Within pegmatite itself pyrrhotite and pyrite occur in several ways: as large pod-like masses (1-foot pyrite pod in the Moody pegmatite, Macon Co., 6-inch mass of pyrrhotite in Beasley No. 1 pegmatite, Macon Co., and ½-pound piece of chalcopyrite in Thorn Mountain pegmatite, Macon Co.), as small clusters of blebs, as minute disseminations, and as films and veinlets. Disseminations and blebs occur chiefly in plagioclase, microcline, and quartz, and are invariably surrounded by a zone of greenish coloration, which is especially prominent in the feldspars. The size of the halo and intensity of the color depend upon the size and abundance of the blebs. Toward the sulfide the green color becomes darker, and a thin black film may lie directly

along the sulfide-feldspar contact (fig. 1). Sulfides are usually much more abundant in pegmatite that has been strongly fractured. Under the microscope the green stained feldspar appears turbid to nearly opaque due to a dark cloudy, very fine-grained alteration product that is white in reflected light. It resembles closely the kaolinitic alteration of feldspar. Abundant fine-

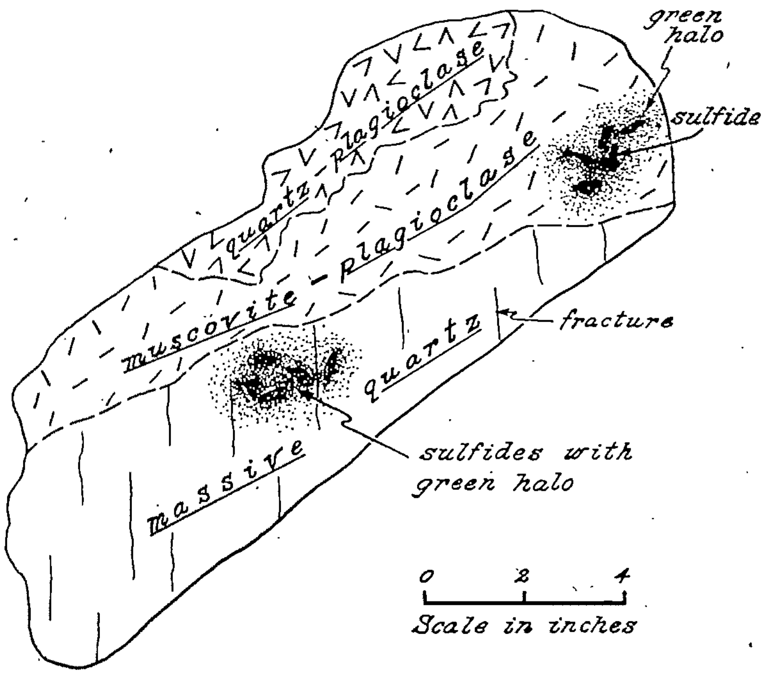


Figure 1. Pyrrhotite blebs in pegmatite, surrounded by zones of green coloration, Bowers deposit, Jackson Co., N. C.

grained sericite also usually accompanies the sulfides, and the green halo is due to a combination of the turbid mineral, sericite, and possibly some melanterite.

Veinlets and films of sulfides coat fractures that cut across plagioclase, quartz, or intergrown quartz-plagioclase rock. Pyrrhotite also appears along feldspar cleavages and forms films along the cleavage planes of both muscovite and biotite. Not uncommonly sulfides form thin coatings around entire mica books, apparently localized along the contact of the books with other pegmatite minerals.

In some pegmatites on Lyle Knob in Macon County veins of

vuggy, sheared quartz containing ¼-inch pyrite crystals have been formed along the cleavages of muscovite books. The crystals are bounded by cube and beveling octahedron faces. Also in these deposits biotite plates lying along fractures in feldspar are coated by pyrrhotite.

At the Tilley mine in Jackson County, pyrrhotite coats the faces of apatite crystals, and at the Big Ridge deposit near Waynesville in Haywood County veinlets of it transect skeletal apatite crystals, one inch across, which consist of a core of quartz, plagioclase, and tourmaline needles and a thin outer shell of light green phosphate. One inch crystals of dark red garnet are veined by stringers of quartz with disseminated pyrrhotite at the Long Branch mine near Cullowhee in Jackson County.

At three deposits, the Big Ridge in Haywood County and the Buoy and Ledford Cove near Franklin in Macon County, pyrrhotite is associated with crystals of diopside-hedenbergite in the marginal parts of the pegmatites. The two minerals usually occur in thin quartz-rich apophyses that contain small, well-developed muscovite crystals. Hedenbergite forms prismatic crystals, as large as ½ x 4 inches, which tend toward parallelism with the apophyse walls. Commonly the crystals are broken, and, where these segments have been rotated or even bent, the rifts are healed by fine-grained quartz and plagioclase or by pyrrhotite. The latter also forms films enclosing the pyroxene crystals. The Ledford Cove pegmatite also is unusual in its high content of biotite, some books which measure as large as 10 x 8 x 8 inches and are partly coated by pyrrhotite.

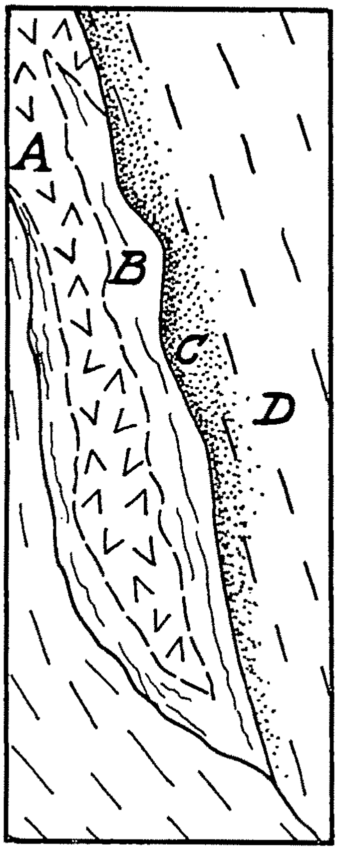
The indices and pleochroisms of the Buoy and Ledford Cove pyroxenes are as follows:

	Buoy	*Ledford Cove*
X	— 1.722, deep gray green	1.693, gray green
Y	— 1.727, deep gray green	1.704, gray green
Z	— 1.743, dark olive green	1.723, olive green

From these data the Buoy mineral contains about 84% of the $CaFeSi_2O_6$ molecule and the Ledford Cove material about 47% of $CaFeSi_2O_6$.

Pyrrhotite and some pyrite also occur in gneissic wall rock near pegmatite margins, where they form minute specks, small blebs, and films along fractures or within quartz stringers.

Later movements along the films have produced slickensides. At some deposits sulfide has been introduced more abundantly along the hanging-wall side of the pegmatite (fig. 2). At the Tilley mine disseminated pyrrhotite has been developed with clusters of chlorite flakes in the wall rock of hornblende-



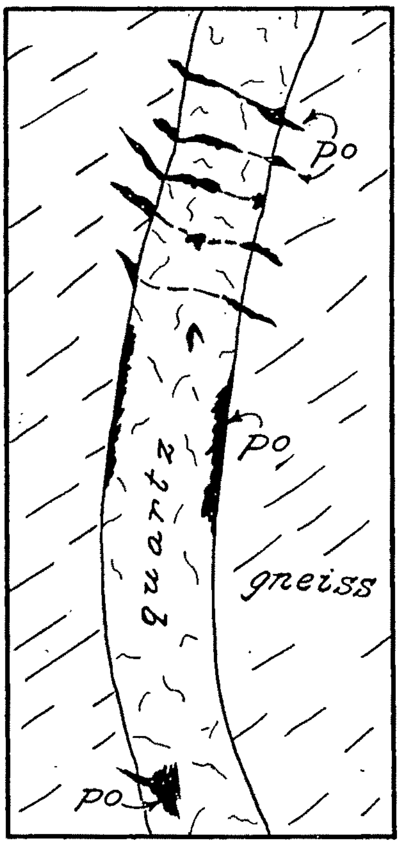


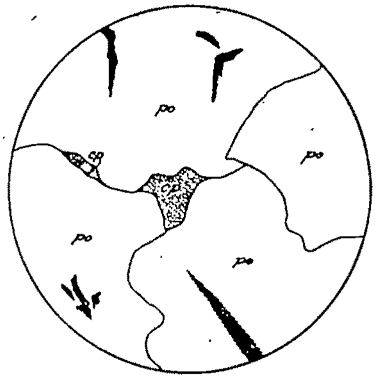
Figure 2. Pegmatite at Rocky Face deposit, Macon Co., N. C. A – quartz and minor plagioclase, B – plagioclase and accessory garnet cut by fractures coated with pyrrhotite, C – pyrrhotite disseminated in gneiss, D – biotite gneiss. Vertical face five feet high.

Figure 3. Ladder veinlets of pyrrhotite cutting quartz vein in biotite gneiss, Tilley pegmatite, Jackson Co., N. C. Vein is five inches long.

biotite gneiss. At the same deposit minute ladder veinlets of pyrrhotite transect quartz stringers in gneiss near the pegmatite margins (fig. 3).

Microscopically the pyrrhotite from the Tilley pegmatite is

rather coarse-grained. Under crossed nicols it exhibits a minor amount of intragranular, rectilinear lamellar structure, which is regarded by Schneiderhöhn and Ramdohr (1931) as the result of exsolution. Small irregular patches of chalcopyrite are localized between pyrrhotite grains (fig. 4). The sequence is pyrrhotite, chalcopyrite, and quartz.



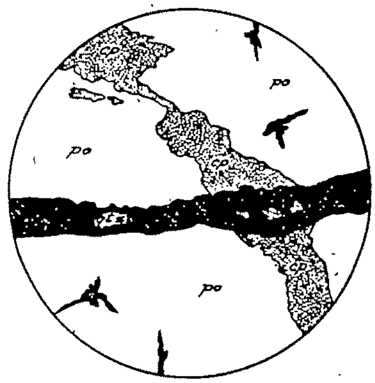


Figure 4. Coarse-grained pyrrhotite (po) with minor exsolution lamellae (lower right), interstitial chalcopyrite (cp), and inclusions of quartz (black). Crossed nicols, magnification 48X. Tilley pegmatite, Jackson Co., N. C.

Figure 5. Vein of chalcopyrite (cp) cutting coarse pyrrhotite (po) and cut, in turn, by quartz (qtz) vein. Magnification 48X. Beasley No. 1 pegmatite, Macon Co., N. C.

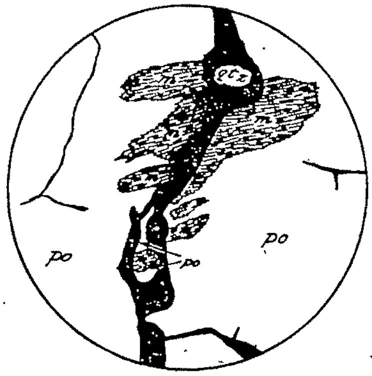
At the Beasley No. 1 pegmatite in Macon County, pyrrhotite, the chief sulfide, contains minor amounts of pyrite, chalcopyrite, and marcasite. The coarse-grained pyrrhotite does not show lamellar structure. Pyrite in anhedral grains lies along contacts between pyrrhotite and quartz. Chalcopyrite is localized along pyrite-pyrrhotite grain contacts and also transects pyrrhotite in irregular veins, which are themselves cut and broken by quartz veinlets (fig. 5). Minute clusters of marcasite blades, probably of supergene origin, have begun to replace pyrrhotite outward from the margins of quartz stringers (fig. 6). The probable sequence is pyrrhotite, pyrite, chalcopyrite, quartz, and marcasite.

From the above relations sulfides in the Franklyn-Sylva district are late minerals that were developed in both pegmatite and wall rock after the former had been consolidated sufficiently to support fracturing. Textural evidence shows that

the sulfides are later than plagioclase, microcline, much quartz (including that of the late crystallizing pegmatite cores), muscovite, biotite, apatite, garnet, and diopside-hedenbergite. The sulfides are considered to be the chief representatives of a weak hydrothermal phase developed within the otherwise generally magmatic pegmatites. These conclusions are supported by Olson and others (1946) who state (p. 9), "The sulfide minerals appear to be among the last to form in the sequence of pegmatite minerals." Sharp (1942) also includes pyrite and chalcopyrite in the youngest group of minerals.

DEPOSITS IN OTHER DISTRICTS

At the Deep Creek No. 1 feldspar deposit in the Bryson City District, Swain County, North Carolina, allanite and sulfides are locally abundant in pegmatite consisting chiefly of microcline, quartz, oligoclase (Ab 82), green sericite, and a small amount of biotite. The rock has been strongly sheared, almost mylonitized in some places, and abundant sericite has been formed along the fractures. Lustrous black allanite occurs in irregular pods as much as an inch long, which are commonly broken and healed by veinlets of fine-grained, flesh-colored feldspar. In polished section the allanite shows strong alteration, being veined by quartz and limonite and grading into patches of a darker gray alteration product. Quartz veinlets cutting it are bordered by pyrite crystals (fig. 7).



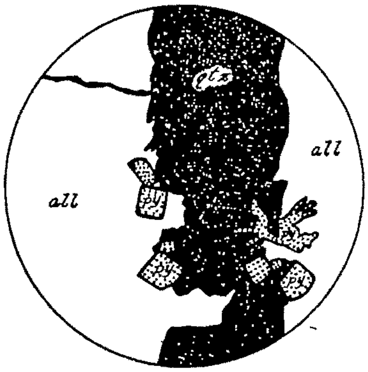


Figure 6. Bladed marcasite (m) replacing pyrrhotite (po) outward from margins of quartz (qtz) vein. Magnification 48X. Beasley No. 1 pegmatite, Macon Co., N. C.

Figure 7. Quartz vein (qtz) with marginal pyrite (py) cutting allanite (all). Magnification 48X. Deep Creek pegmatite, Swain Co., N. C.

Pyrrhotite forms nodules as much as four inches long. Polished sections show that it is very coarse-grained and slightly dichroic, with a well-developed structure of sub-parallel, curving blades under crossed nicols. These resemble the cataclastic lamellae or "Zerknitterungslamellen" of Schneiderhöhn and Ramdohr (1931, fig. 60, p. 135), and their presence probably indicates that shearing followed the formation of pyrrhotite. Cubes of slightly anisotropic pyrite are confined to the pyr-

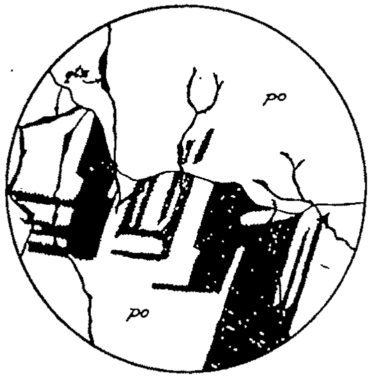


Figure 8. Pyrite (py) cutting pyrrhotite (po) and quartz (qtz), which also transects pyrrhotite. Magnification 48X. Deep Creek pegmatite, Swain Co., N. C.

Figure 9. Lamellar exsolution structure (shaded) in coarse-grained pyrrhotite (po) cut by quartz (qtz) veinlets. Crossed nicols. Magnification 48X. Mill Race pegmatite, Cleveland Co., N. C.

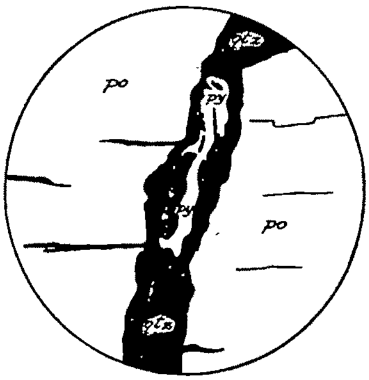
rhotite margins and to the vicinity of fractures. Locally, pyrite veins pyrrhotite and sends thin stringers into quartz (fig. 8). Small blebs of chalcopyrite occur interstitially between pyrrhotite grains or between pyrrhotite and quartz. The sequence appears to be allanite, pyrrhotite, chalcopyrite, fracturing, pyrite, quartz, sodic plagioclase, sericite, and limonite.

Sulfides are locally abundant as accessory minerals in pegmatites of the Shelby district, North Carolina. The Foster mine in Cleveland County contains pyrite veinlets in smoky quartz. In vuggy parts of the veinlets pyritohedrons have crystallized. Crusts of marcasite occur along fractures in massive white quartz of the core, and small flattened marcasite "suns" coat feldspar cleavage surfaces. Disseminated pyrite also occurs in the wall rock.

The Mill Race pegmatite near Boiling Springs in Cleveland County contains abundant pyrrhotite, which replaces feldspar

and muscovite. Pseudomorphs of pyrrhotite after muscovite crystals reportedly have been found. Feldspar and quartz surrounding the sulfide have the usual green stain. Fist-sized masses of pyrrhotite are not uncommon and along fractures are altered to marcasite. In polished section the coarse grain of the pyrrhotite and the unusually well-developed lamellar exsolution structure are conspicuous (fig. 9). Minute pyrite particles are interstitial to it, and irregular quartz veinlets transect it. The sequence is pyrrhotite, pyrite, quartz, and marcasite. Pyrrhotite also is disseminated in the wall rock.

Abundant gray calcite replaces microcline at the Bowen pegmatite, near Double Shoals in Cleveland County. Pods of pyrrhotite, several inches long, are associated with two-inch cleavage pieces of calcite, fine flakes of green sericite, sericitized white sugary sodic plagioclase, muscovite plates, crusts of fibrous black tourmaline, and vugs lined with muscovite and



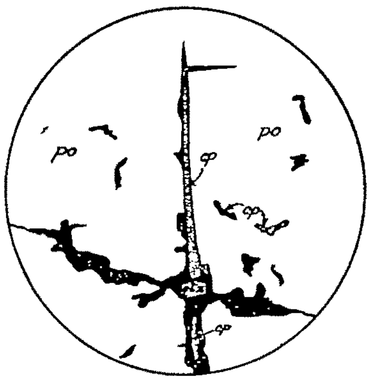


Figure 10. Quartz vein (qtz) with corroded pyrite (py) transecting pyrrhotite (po) and extending stringers along basal {001} parting. Magnification 48X. Bowen pegmatite, Cleveland Co., N. C.

Figure 11. Chalcopyrite (cp) and quartz (qtz) veining pyrrhotite. Magnification 48X. Bowen pegmatite, Cleveland Co., N. C.

plagioclase crystals. The pyrrhotite is typically very coarse-grained, but lamellar exsolution structure is absent. Corroded pyrite occurs in quartz veinlets which project minute apophyses along the {001} parting of pyrrhotite (fig. 10). Chalcopyrite and quartz form thin stringers and small curved replacement blebs in pyrrhotite (fig. 11). The sequence appears to be pyrrhotite, pyrite and quartz, chalcopyrite and quartz, and quartz.

Discussion

Sulfides, especially those of iron and copper-iron, are not uncommon as accessory minerals in very minor amounts in pegmatites ranging in composition from granitic to ultramafic Landes (1933, p. 97) has recognized, however, that pegmatites of intermediate composition (syenitic) may contain rather abundant sulfides as a characteristic accessory assemblage of the hydrothermal phase. Although sulfides may occur locally even in relatively large masses[8] in hydrothermally altered pegmatites of granitic composition, they appear to be more widespread and abundant in pegmatites whose compositions range from quartz dioritic to quartz monzonitic. In several districts, with which the writer is particularly familiar, such as those of some of the southeastern states and those of Montana where relatively few pegmatites of true granitic composition occur, sulfides, particularly pyrite and pyrrhotite, are moderately abundant and form the most characteristic and widespread element of the hydrothermal accessory mineral suite. In these quartz diorite, granodiorite, or quartz monzonite pegmatites, the hydrothermal phase is almost invariably subordinate and restricted in the variety of its mineral components. Usually absent are such "typical" granitic pegmatite accessories as cleavelandite, beryl, lithium minerals, phosphates, and rare earth compounds. Dunham (1935) has described similar pegmatites in the Organ Mountains, New Mexico, which are associated with quartz monzonite and contain a strongly developed terminal sulfide phase. Among the accessories is diopside hedenbergite.

Landes (1937) has contrasted the pegmatitic offspring of granitic magmas with those of intermediate magmas and has concluded (p. 559) that the latter "during their crystallization sequence pass through a minor pegmatite phase before entering the hydrothermal phase." This may be true in many districts but cannot be accepted for this magma type as a whole. Certainly in the districts cited above, which embrace relatively large areas and large intrusive bodies such as the Whiteside quartz diorite-granodiorite and the Boulder batholith there are strongly developed pegmatites of intermediate composition

[8] Note, for example, the occurrence of a six-foot chalcocite pod in the Mica Lode pegmatite, Eight Mile Park, Colorado (Heinrich, 1948, p. 564).

with a weak hydrothermal sulfide phase. Possibly the difference between the two magma types is partly only apparent and stems from:

1. Lack of quantitative data on the bulk composition of pegmatites. Many so-called "granitic" pegmatites, on close analysis, have been found to contain considerable primary plagioclase.
2. Lack of interest in pegmatites poor in spectacular hydrothermal minerals, as the intermediate pegmatites commonly are.
3. The level to which erosion has exposed the district. This may determine to some extent whether veins or pegmatites crop out in abundance. Presumably those districts eroded to deeper horizons would show pegmatites in greater numbers.

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CUBIC PSEUDOMORPHS OF QUARTZ AFTER HALITE IN PETRIFIED WOOD

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ABSTRACT. A portion of the Sweet Home, Linn County, Oregon, petrified forest east of the town of Holley has yielded petrified wood which is unique because of its inclusions. These inclusions are white or gray cubes, some more than six millimeters in size, consisting of a mosaic of quartz. They are found in *Platanus*, the sycamore, and more commonly in large concentric tubers which lack the cross grain due to wood rays. Many quartz cubes have hollow centers which are square in cross section. Some of the cubes are modified by the octahedron.

A study of the replacement leads to the conclusion that the quartz is pseudomorphous after skeletal halite crystals. The presence of high concentrations of sodium chloride, necessarily prior to the petrifaction of the wood, indicates the probable existence of a marine lagoon, in this case most likely during the Oligocene epoch. The generally accepted conclusion that hopper-shaped or skeletal halite develops only on an evaporating surface is refuted by this occurrence because the halite is distributed all through the wood.

INTRODUCTION

IN the region adjacent to the town of Sweet Home in Linn County, Oregon, there is a large area containing petrified wood. The exact size of the area is not known, but the largest concentrations of petrified wood are distributed over some 20 square miles. Petrified wood is common in the Willamette Valley but in the Sweet Home area there is an occurrence which is unique in that some of the specimens contain inclusions of quartz which are cubic in shape (pl. 1, fig. 1). The best specimens are to be found in a small area about 1½ miles east of Holley. A study of the inclusions, which are pseudomorphs, was made in order to determine their genesis and to throw some light on the geological conditions existing at the time of their formation.

The presence of inclusions in petrified wood has been noted by several investigators. Probably the most unusual inclusions previously described are the small elongate objects with hexagonal cross-sections found in opalized wood from Santa Maria, California, which Rogers (1938) explained as excreta of termites. Another type of inclusion, common in many Oregon localities, consists of tube-like bodies of chalcedony formed by filling of borings left by a species of *Teredo*. Material with nicely banded chalcedony in the borings, such as that

found east of Roseburg, Oregon, on the North Umpqua river, is in demand by mineral collectors. The pseudomorphs described in this paper are of neither of the above-mentioned types and are quite certainly inorganic in origin.

ACKNOWLEDGMENTS

The writer is indebted to Mrs. Ted Gordon of Salem, Oregon, for first calling his attention to the material described in this paper. Professor George Beck of the Central Washington College of Education kindly sectioned and identified several specimens of the petrified wood. Permission to collect material on his property was granted by C. C. Swigart. Finally, the writer wishes to acknowledge financial assistance in the preparation of the paper from the Graduate School of the University of Oregon.

SWEET HOME PETRIFIED FOREST

The Sweet Home petrified forest has received very little attention. Dake (1940) noted the occurrence and described some of the best spots for observing the trees. Beck (1944) studied some of the wood and reported the probable presence of oak, sycamore, alder, beech, and a conifer which apparently was *Trochodendron*. Beck was amazed at the large number of hardwoods present and he was convinced that many of the trees must have become extinct and left no living counterparts.

All of the fossil woods studied from the Sweet Home area are silicified, quartz and chalcedony being the replacing minerals. Opal seems to be almost entirely lacking. In most specimens, the original wood structure is beautifully preserved. All of the wood containing the inclusions to be discussed was found as float, although in several areas petrified trees up to six feet in diameter are found in place. All of the observed trees were embedded in tuff or agglomerate. No pre-Tertiary formations are known in the area and it is safe to assume that all of the woods are of Tertiary age. Recent finds of excellently preserved leaves, closely associated with the petrified trees, make this an unusually good locality for a study of Tertiary flora. Work of this type is now underway.

No attempt was made to study the generic distribution of the petrified wood devoid of quartz pseudomorphs; the fol-

lowing discussion is concerned only with those relatively rare specimens which contain the cubic inclusions.

The term "petrified wood" used throughout this paper requires some qualification. Most of the specimens, some up to 20 cm. in diameter and containing quartz pseudomorphs, show no evidence of longitudinal grain (long fibers) or cross grain due to wood rays. From study of sections of this material, Beck[1] concluded that it was not true wood but the petrifaction of some type of concentric tuber. In general, geologists in using the term "petrified wood" do not attempt to draw a fine distinction between true woods and pith-like or tuberous plants. In this case, further search yielded some material, with quartz pseudomorphs, which permits proper use of the term "wood." A specimen from a tree which was probably about 15 cm. in diameter showed distinct rays. According to Beck,[1] the wood is a "diffuse porous hardwood with compound rays" and most likely is that of *Platanus*, the sycamore. *Platanus* has been found before in the area, although this is the first time that it has been seen to contain quartz pseudomorphs. Petrifaction of the wood has also taken place by replacement of the wood with quartz.

DESCRIPTION OF QUARTZ PSEUDOMORPHS

As shown in the illustration (pl. 1, fig. 2), the quartz pseudomorphs are square or nearly square in cross section and in three dimensions are usually equidimensional or cubic. The frequency with which true cubes, rather than malformed ones, are found leaves little doubt that the replaced mineral was cubic. In the specimen of *Platanus* mentioned above it was found that some of the square cross-sections had truncated corners. Because this might have been produced by modification of a cube by either a dodecahedron or an octahedron, search was made for complete crystals in order to determine the correct interpretation. Several complete crystals were found, and on these the modification was observed only at the cube vertices, indicating that it was due to the octahedron. This accounted for the fact that many of the sections of the cubes failed to show the modification. The presence of the octahedron is significant in increasing the evidence that the modified form was isometric.

[1] Personal communication.

Many of the crystals are skeletal, the cubes having hollow centers. The cavities usually appear as square holes on a cube face and many of them are partly filled with euhedral quartz growing inward from the walls of the skeletal cube.

The arrangement and orientation of the quartz pseudomorphs are striking. The crystals are massed along the outer edge of the wood, often making it difficult to see the original structure of the bark, if any were present. Closer to the heart of the wood the cubes are more widely dispersed and consequently can be studied better. The annular rings spread around the cubes, indicating that the original cubic mineral had sufficient crystallizing force to induce the spreading (pl. 2, fig. 4). In sections of the wood cut either transversely or longitudinally, almost all of the sections of the cubes are square or rectangular, and only occasionally are triangular sections found. This indicates that most of the cubes in these sections are cut perpendicular to a 4-fold axis rather than perpendicular to a 3-fold or 2-fold axis and shows a preferred orientation of the cubes. This orientation may well be governed chiefly by the annular rings. Also of interest, but not easily explained, is the fact that the cavities in the skeletal crystals are parallel to the longitudinal axis of the wood.

DETERMINATION OF REPLACED MINERAL

The cubic crystal form implies that quartz replaced an isometric or pseudo-isometric mineral. Although there is some malformation of a few cubes it is not sufficient to cause one to think that the original crystals could have been rhombohedrons, such as those described by Adams (1920) where dolomite replaced wood.

Some of the most common minerals to be found in cubes are pyrite, fluorite, galena, and halite. In addition, anhydrite and quartz are sometimes found pseudo-cubic. The possibility of the original mineral being quartz with a large development of the rhombohedron ($rr' = 85° 46'$) giving a pseudo-cubic appearance can be disregarded, since aside from the fact that modification by the octahedron has been observed, it is unlikely that the original quartz crystal would be replaced by finer grained quartz. Fluorite in distinct separate crystals would not be expected to occur in petrified wood and there is no known source for the fluorine in this area. Likewise there is

no evidence of lead minerals in the area, and there is no reason to believe that the quartz is pseudomorphous after galena as described by Emerson (1896, p. 139) from Massachusetts where hollow cubes were found with the quartz in parallel ridges due to penetration into the cleavage planes of the galena. Limonitic stains are generally absent and there is no evidence to indicate the former presence of pyrite in the wood. Also, as will be shown, the quartz definitely is a replacement and not merely a cast due to filling of the impression left by the removal of original material. Consequently it cannot be assumed that pyrite was removed and quartz later filled the void.

The two most likely minerals to be replaced to yield the quartz pseudomorphs are anhydrite and halite. Only occasionally does anhydrite occur in euhedral crystals, but it may do so and assume a pseudo-cubic habit when the pinacoids are the dominant faces. Rarely, also, anhydrite is pseudomorphous after halite and therefore in cubes, but there is no evidence of this replacement. From a physical-chemical standpoint it would be possible for anhydrite to form under the conditions which probably existed at the time of the formation of the cubic crystals. Although usually anhydrite crystallizes above 66°C, with gypsum forming below this temperature in pure solutions, it is known that if considerable NaCl is present in the solution the critical temperature for the crystallization of anhydrite may be as low as 25°C. In spite of the fact that it would have been possible for anhydrite to form, there is no positive evidence to indicate that this mineral ever existed in the wood.

All of the evidence obtained from a study of the pseudomorphs leads to the conclusion that the quartz is pseudomorphous after halite. The strongest confirmation of this is the fact that the original mineral often occurred in skeletal or hopper-shaped crystals, a habit which is typical and common only in halite, among the minerals considered above.

The term 'hopper-shaped" as applied to skeletal crystals of halite has attained very general usage, but as a result of

EXPLANATION OF PLATE I

Fig. 1. Quartz pseudomorphs standing in bold relief on surface of petrified wood.

Fig. 2. Quartz pseudomorphs after skeletal halite exhibiting square central cavities, X 1.

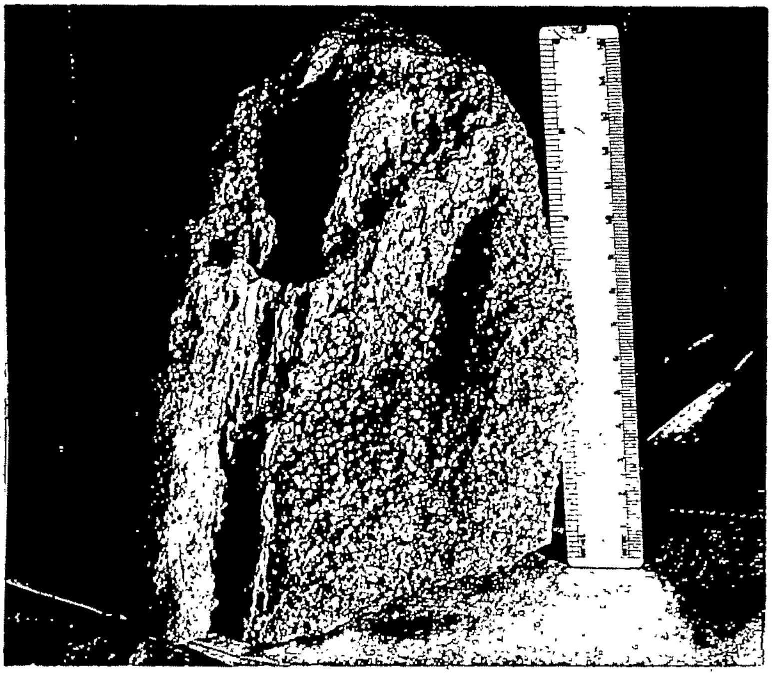

FIGURE 1

FIGURE 2

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

never having been carefully defined, many different skeletal types are included. The word "hopper" usually refers to a funnel-shaped container and consequently it would seem logical to confine the term "hopper-shaped" to those skeletal crystals which have funnel-shaped cavities. There are two general types that fulfill this requirement. The type which is usually pictured in mineralogy textbooks (Dana, 1892, p. 154) is a cube with an inverted pyramidal depression which descends by steps on each cube face. Another type consists of a single "hopper" presenting a V-shaped cross section and is due to the offsetting of the cube units during growth. This is the type described by Mendeleeff (1891, p. 416), "the salt often separates out on the surface as cubes, which grow on to each other in the form of pyramidal square funnels." In many cases it is difficult to determine whether the internal cavity is funnel-shaped and the general term "skeletal" is preferable under these circumstances. In the case of the quartz pseudomorphs described here, the original halite was of the single cavity type with a square surface opening and a cavity that closed at the bottom. Any step-like character of the walls of this cavity is now hidden by a coating of small euhedral quartz crystals. However, there is little doubt but that the halite was of the second type of hopper crystal mentioned above, that is, the single hopper. Further evidence of this is the offset in the crystal walls, so characteristic of this type of crystal growth.

A comparison of a skeletal crystal of halite with a quartz pseudomorph removed from the petrified wood is shown in plate 2, fig. 3. It is to be noted that the cavity in the center of the quartz pseudomorph produces a square opening on the cube face, just as is the case with the skeletal halite crystal. The presence of the square central hole is evidence that the quartz replaced the halite rather than filling the

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EXPLANATION OF PLATE 2

Fig. 1. Photomicrograph of quartz pseudomorph showing alignment of quartz normal to edges. Crossed nicols, X 25.

Fig. 2. Quartz pseudomorph with quartz aligned parallel to edge. Arrangement probably determined by original cleavage of halite. Crossed nicols, X 25.

Fig. 3. Comparison of quartz pseudomorph from petrified wood (above) with skeletal halite crystal (below), X 5.

Fig. 4. Section of petrified wood with quartz pseudomorphs showing spreading of annular rings by halite before pertification, X 1½.

cavity as a cast, since in the case of partial cavity filling a circular or irregular void would be expected. A study of many thin sections gave further evidence that the replaced mineral was halite. Plate 2, fig. 2 shows sharp breaks parallel to the cube face, with anhedral quartz crystals arranged in rectangular blocks. This is probably evidence of the cubic cleavage of the halite. In other examples (pl. 2, fig. 1) the quartz is aligned normal to the cube face and produces a striking orientation.

Burt (1929) described some petrified wood from Brazos County, Texas, in which silica was pseudomorphous after either pyrite or halite. Dr. H. B. Stenzel, University of Texas, kindly made a specimen of this material available for study. Unlike the Holley petrified wood, the pseudomorphs occur only on the surface of the wood, occupying the position of the bark. Moreover, as pointed out by Burt, the evidence is inconclusive as to what the replaced mineral might have been. Not only pyrite or halite suggest themselves, but even fluorite is a possibility.

The literature contains numerous references to pseudomorphs after halite by minerals other than quartz. Obenauer (1930) describes pseudomorphs of gypsum after large distorted cubes of halite (15 x 12 x 8 cm.) in a clay pit at Saarbrucken. Emerson (1896, p. 144) mentions calcite pseudomorphs after halite in the Triassic shales of Massachusetts, at one time mistaken for chiastolite. Hopper-shaped cavities have been described by Hawkins (1928) from the red Triassic shales of New Jersey, and both Dropsy (1938) and Merritt (1936) described hopper-shaped casts of dolomite after halite, from France and Oklahoma respectively. Shrock (1948, pp. 146-149) cites several other references to pseudomorphs after halite in sediments and discusses their value in determining the top and bottom of beds. Although quartz pseudomorphs after halite in wood are rare, it is evident that pseudomorphs after euhedral and hopper-shaped halite are relatively common in nature.

CONDITIONS FAVORING FORMATION OF HALITE

As there can be little doubt that the replaced mineral was halite, the question arises as to the unusual conditions which existed prior to the petrifaction. The portion of the forest

in which the trees lived must have been covered to some extent by water with a high NaCl content. Such saline bodies might have been salt lakes or salt pans due to evaporation under conditions of internal drainage, saline crater lakes, salt springs, or they might have been arms of the sea cut off and forming lagoons or saline estuaries. There are no known saline strata in the Holley area that might produce local salt springs so this method of bringing in the salt is unlikely. Nor is there evidence of saline volcanic craters in the area although extrusive and pyroclastic rocks are common. The most probable environment for burial of the trees was either in a salt lake or marine lagoon. Direct evidence confirming either of these latter conclusions is lacking.

As has been mentioned, the Sweet Home forest has many petrified trees in situ, but unfortunately none of these examined contains the quartz pseudomorphs. The exact source of the wood containing the pseudomorphs although not known is probably not far away, because the occurrence is limited to a small area. This locality at Holley is just east of the line which marked the eastern edge of the Oligocene sea according to Lowry (1947). Vokes and Snavely (1948) in studying the fossils in a quarry 12 miles due west of Holley found in the fine tuff along with abundant marine Oligocene fossils, well preserved imprints of what they interpreted as halite crystals. They considered the presence of the fossils and halite imprints in the same deposit as evidence of shoreline conditions. These observations strengthen the possibility of the wood at Holley having undergone inundation in an arm or lagoon of the Oligocene sea.

Dunbar (1924) described an association of halite and petrified wood in Kansas, which, although not strictly analogous because the halite and wood are not together, indicates an environment that might have been similar in some respects to that at Holley. According to Dunbar, the Permian Wellington shales at Insect Hill near Elmo, Kansas, contain a bottom zone of shale with calcareous bands that had salt "hoppers" in them, up to 10 inches across the face. Over this is a black shale with scores of silicified stumps, and above this a marly limestone containing well-preserved insects. Dunbar interprets this occurrence as due to first, a marine body of water surcharged with NaCl, second, temporary emergence permitting

the growth of trees in a swamp, and third, submergence again. This took place along the eastern margin of the Kansas sea, and gave rise to "dead sea" and lagoonal conditions.

At Holley, the occurrence of considerable tuff and basalt indicates volcanic activity along with the marginal sea conditions. Assuming that the wood with pseudomorphs was originally enclosed in tuff, similar to the wood in place, it seems probable that the trees grew in swamps not far from the Oligocene coast, and that they were submerged in a shallow lagoon in which NaCl became concentrated. During this stage the trees were killed and the halite crystallized in them. Volcanic ash was then deposited in the lagoon, completely enveloping the trees.

The presence of pyroclastic material closely associated with the petrified wood indicates the possibility of hot water being important in the silicification of the wood. The fact that silicification is entirely by crystalline or cryptocrystalline silica rather than opal also tends to indicate a higher temperature for the silica-bearing solutions. In this connection it is interesting to note that NaCl is one of those rare salts whose solubility in hot water is not appreciably greater than in cold water and consequently removal of the NaCl would not be greatly hastened under these optimum conditions for the transportation of silica.

The mechanics of the formation of the halite crystals in the wood is interesting. Without doubt the crystals formed before petrifaction started, as indicated by the spreading apart of the wood fibers and by the replacement both of the wood and the halite by silica.

It seems probable that the halite crystallized after the plant died, even though there is ample evidence in nature of living plants taking salts from the soil and concentrating them. Grabau (1920, p. 247) gives as examples of the latter the Argentine jume or saltwort, the ashes of which yield 19% NaCl. In the Nebraska Sand Hill region the NaCl content of some lakes is up to 40% NaCl and this has been explained as due to leaching of burned plants (Grabau 1920, p. 259). Although salts may form as a crust on the plant, actual crystallization of larger NaCl crystals within the plant such as occurs in the Holley wood is not known.

An excellent example of dried wood absorbing salt solutions

is seen at present on the Bonneville Salt Flats on the western shore of Great Salt Lake, Utah. Here according to Dr. Orlo Childs[2] salt water moves up into the bases of telephone poles and crystallization expands the poles until they burst. The mechanics of the movement of the salt solutions up the poles is not known but the fact that the poles are dry and strong above 3 or 4 feet indicates a limiting factor such as the force of capillarity. Capillarity can satisfactorily account for a rise of this magnitude.

In the case of the Holley petrified wood, the concentration of the halite crystals near the bark indicates that the salt solutions were absorbed from the periphery rather than rising through the center. The even distribution of the crystals around the periphery proves that the trees were completely covered at the time of halite crystallization and solutions had access from all sides.

There can be little doubt that the crystallizing halite had sufficient strength to force the plant tissue apart as shown in the specimens here described. Becker and Day (1905) concluded from a study on crystallization of alum that its crystallizing force is of the same magnitude as the resistance which the crystals offer to crushing stresses. Harris (1909, p. 23) in applying these observations to halite determined that a 4-inch cube withstood a confined pressure of 50,000 pounds without even cracking. It might be assumed that a hopper-shaped crystal would not have great crystallizing force, but in the experiments of Becker and Day the face of the crystal in contact with the lower surface of the vessel was found to be a terraced cup form and the pressure exerted by the crystal was distributed along a thin edge throughout its growth. It is evident then, that a pulpy or rotten condition of the wood was not necessary to explain the forcing apart of the annular rings because ample strength of crystallization of halite could account for the phenomenon. This, of course, does not preclude the possibility that some softening had occurred, but the retention of delicate radial and growth structures in some of the specimens indicates that decay had not advanced far.

The formation of hopper-shaped crystals of halite was explained by Mendeleeff (1891, p. 416) as occurring in the upper

[2] Personal communication.

layer of a brine with subsequent sinking and continued growth at the surface of the brine. Mellor (1922, p. 529) states "When the crystals form on the surface of evaporating brine, distinctive hopper-shaped crystals resembling hollow quadrilateral pyramids are developed; the inner surface appears to be arranged in a series of steps." Hopper-shaped halite crystals have generally been assumed to indicate that evaporation of the NaCl solution took place at the surface of the solution in contact with air, or in the case of halite in clay, the solutions evaporated on mud surfaces. The occurrence described here is interesting in that it indicates skeletal or hopper-shaped crystals can form under very different conditions, with complete confinement.

Considerable work has been done on the subject of habit variation in crystals, and halite has been used in these studies probably more often than any other mineral. It has long been known that halite grown from solutions containing urea exhibits a preferential growth of the octahedron rather than the usual cube. The importance of impurities in the solution has been demonstrated by Egli (1949, p. 272) who found that small amounts of impurities actually produce larger and better crystals of halite than pure solutions, while larger concentrations of impurities frequently modify the crystal habit. Retgers (1892, p. 270) showed that if a solution is thickened by the addition of gelatine, dextrine, or glycerine, the growth of skeletal crystals of NaCl is promoted. In the case of skeletal crystals of NaF, Frondel (1940, p. 346) found that a low OH ion concentration aided their formation. Experiments which may have a bearing on the Holley occurrence were performed by Royer (1930, p. 190) who found that modifications of crystals, especially to forms of lower symmetry, were produced by brown solutions from peat which were rich in humic materials. Although we cannot be certain of the chemical composition of the solutions from which the halite crystals formed at Holley, it seems probable that impurities in the form of humic acids might readily account for the anomalous occurrence of skeletal halite crystals within the wood.

CONCLUSIONS

A study of petrified wood with cubic inclusions from Holley, Oregon, has established the fact that the inclusions are quartz

pseudomorphs after halite. The presence of halite crystals in wood, which later underwent petrifaction, permits interesting speculation concerning the conditions at the time of growth and later preservation of the trees. Probably during Oligocene time the trees were inundated by a shallow marine lagoon and enclosed by a fall of volcanic ash. High salinity of the lagoon caused crystallization of NaCl in the tree stumps and silicification of both the halite and the wood took place, beautifully retaining the structure of both.

The NaCl solutions were probably carried into the wood by capillarity and there was some orientation of the halite, governed by the annular rings. The formation of skeletal halite crystals usually takes place at evaporation surfaces and their presence deep within the wood requires special explanation. There is a possibility that organic compounds within the wood were responsible for the unusual habit.

This occurrence is of interest because of the fine preservation of the halite crystal habit in the quartz pseudomorphs and because the data obtained from studying the material aid in reconstructing a picture of the environment of petrification.

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GULLIES FORMED BY SINKING OF THE GROUND*

A. F. BUCKHAM AND W. E. COCKFIELD

ABSTRACT. Rubey (1928) suggested that many gullies in semi-arid regions are formed by sinking of the ground, and not by surface erosion. He postulated a mechanism involving washing out of fine material, and development of subsurface tunnels, followed by caving. He had no direct evidence of this mechanism. The writers studied an occurrence where the tunnels and other features could be seen, thus confirming Rubey's theory. They describe the occurrence, and offer observations on this little discussed method of erosion.

TWO decades ago Rubey (1928) proposed a theory of the origin of the flat-floored scarp-bordered valleys common in the arid and semi-arid western plains. He described how these gullies show at their head crescent-shaped cracks whose "horns" point down slope, the cracks becoming scarps one-half to four feet high a little below the head.[1] The "horns" of the crescents in places extend into subparallel cracks bordering the gully floor, and elsewhere curve in and join, making elliptical depressions whose maximum diameter ranges from four to fifteen feet. These features, which indicate a movement of near surface material chiefly vertical but also slightly horizontal, persist for as much as a mile down the gully. Beyond this the effects of surface erosion become perceptible but for several thousand feet farther down the valley sinking of the gully floor, not surface erosion, is the chief factor in valley growth. The elliptical depressions deepen by continued sinking, and "coalesce by concentric cracking, tunneling and headward erosion until they become a loosely connected chain of pits or water-holes similar to the lines of water-holes common throughout the semi-arid west." Rubey adduces further evidence that suggests sinking is effective still lower in tributary gullies, and also in the main streams, but that its effects are masked by those of surface erosion.

The explanation of the process is uncertain although clearly due to ground sinking. The observed features indicate "that

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[1] Sharpe (1938a) has illustrated these phenomena, and applied the term "stepped crescents" to them, later (1938b) stating that they are common on the High Plains from Texas to Montana.

the movement of ground-water and soil particles is downward for a few feet and then, presumably at a temporary water table, virtually horizontal." Rubey suggests, although he has no direct evidence of it, the following. A "process of washing out of material seems to the writer the best explanation of the elliptical depressions and perhaps of the vertical scarps also. In loose sandy soils with a low water table and in soils deeply cracked by repeated droughts, percolating water would carry with it the finer clay and silt particles and eventually develop small passageways. Miniature tunnels would form just below the temporary ground-water level of the rainy season, and once started, the effects would be cumulative. As these small passageways grew, more vigorous subterranean erosion and transportation would be possible. Subsidence of the roofs over the tunnels would develop surface depressions which would concentrate rain water and intensify percolation and erosion. Loose wet soil would gradually move in from both sides to fill the tunnels and the ground would sink, perhaps as a flat gully floor. That is, the soil would creep to the middle of the gullies to fill the tunnels, thus causing the sod at the margins of the moving mass to crack, and the ground inside the marginal cracks might sink evenly. In turn, cracks formed by soil creep would localize percolation and thus start new tunneling."

No new evidence bearing on the subject appears to have been published until the writers' description of just such a system of sink-holes and tunnels as was postulated by Rubey. (Cockfield and Buckham, 1946). They were not then aware of his paper, and recently came upon it by chance. Since the process he postulates may be of some importance, and since the connection between the two papers is not obvious, it is considered worth while to summarize briefly our findings.

The features seen were studied at Kamloops, British Columbia, (51°N, 120°W). This part of British Columbia has an arid climate but is subject to torrential rains of brief duration, which causes local flooding, and much local rapid erosion. The features occur in a Pleistocene deposit known as the "White Silts," horizontally bedded, vertically jointed, uncemented material whose particles are angular, 0.01-0.06 mm. in diameter, and composed chiefly of feldspar and quartz. Where studied the silts occupy prominent terraces on either side of

South Thompson valley; the tops of the terraces being about 0.4 mile wide and standing 300 to 400 feet above the main valley bottom. The terraces have been thoroughly dissected by numerous branching gullies, with steep to vertical walls, and floors of considerable width. The floors are nearly flat transverse to the gully, but have considerable grade downstream. In the main gullies a narrow, vertically walled trench has been excavated in the valley floor and carries the main run-off. Thus both climatic and topographic features here are similar to those described by Rubey.

Numerous sink-holes occur in the silts. They are large funnel-shaped depressions, circular at the top, with varying diameters, fifty to one hundred feet being fairly common. Exceptionally they are as much as fifty feet deep, and usually each has a nearly vertical outlet three to five feet in diameter, connecting with a nearly horizontal underground passageway in places three to four feet high. They are most common near the edges of the steep slopes along the main gullies or at the terrace fronts. In many instances their outlets were found one-half to two-thirds of the way down the gully walls. They also develop along shallow gullies, as a line of depressions separated by comparatively narrow rims. With the collapse of such rims, a continuous gully is formed at the level of the underground passageway, when the whole process may be repeated, lowering further the gully bottom. Collapse commonly gives rise to steep or vertical walls.

The following method of formation is suggested for the sink-holes.[2] The silts have a certain amount of permeability, apparently quite variable from place to place. Water, at times of spring melting and after the infrequent storms, percolates into the silts and travels downward until it reaches a temporary water table, when it travels more nearly horizontally until it reaches a point on a gully wall or otherwise returns to ground surface at a lower level. This forms a body of saturated silt, from the lower end of which water carrying silt emerges. Commonly a block of silt suddenly slides out, and a tunnel is formed running back into the silt body. It appears

[2] H. S. Bostock, Geological Survey of Canada, in discussions with the writers contributed to their understanding of the formation of these features.

that a "free face" of some sort is necessary to initiate the process. Of course, once an underground passageway has formed it itself provides a free face throughout its length.

We have, then, the surface water tending to disappear underground and travel some distance below the land surface, at first dropping steeply and then travelling more nearly horizontally. At a free face, blocks of saturated silt drop out forming the beginning of underground channels which rapidly work their way inward from the point where the water discharges from the bank or steep gully face. Once a passageway is opened up, water flows through it as a stream, much more freely than when it was percolating through the silt. The silt, because of its extremely fine grained character, is readily carried in suspension by the stream. The stream greatly increases the rate of erosion and the underground channel is thus enlarged until the roof can no longer support the load and parts of it fall in. There are thus formed one or more funnel-shaped depressions, which in turn serve to collect more water from the surrounding area and pass it into the underground system. As the process continues the rims between adjacent sink-holes collapse, thus forming a continuous gully.

It should be pointed out that the White Silts were first studied by G. M. Dawson in 1877 and since that time much geological work has been done in the area. Nevertheless, the presence of the sink-holes was not noted until the writers' visit in 1945. It may be that closer search in the High Plains region of the United States will reveal other occurrences of these features. Probably they would be most easily recognized in the more arid regions, since, at Kamloops, they are seen best where only precipitation falling on the terraces themselves is effective in eroding. Where water from higher slopes crosses the terraces, the features are, if present, obscured by the effects of stream erosion. It is possible that the process is also operative in more humid regions than those here discussed, but that its results are completely masked by those of stream erosion.

Very similar features, for which an explanation substantially the same as the foregoing is given, are found in the loess areas of China. They have been described by Fuller (1922). The White Silts bear strong resemblances to loess in their composition, in some textural features, and in the physio-

graphic forms which they assume. The well-known occurrence of extensive deposits of loess, and of other wind-blown material in the Great Plains and adjacent areas of the United States is a suggestive parallel. Whatever the origin of the materials in which these features form, it is felt that the peculiar nature of the silts had much to do with the formation of the sink-holes at Kamloops. It is considered that studies of the composition and physical properties of the materials in which such features occur will be of importance in further elucidating the problem.

A process postulated by Rubey to account for the formation of certain gullies, not actually known by him to occur, has therefore been seen and studied; that such a process will produce the given results, has been confirmed. Neither the writers, nor Rubey, contend that this is the only way in which gullies may form under the stated conditions. They do contend that it is one way, and possibly an important way, in which such gullies may be formed.

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WHAT TO EXPECT FROM A STANDARD SPECTROCHEMICAL ANALYSIS OF COMMON SILICATE ROCK TYPES

L. H. AHRENS

ABSTRACT. The minor constituents likely to be detected and determined by a standard spectrochemical analysis of common silicate rock types are discussed and tabulated.

A petrologist is well aware of what to expect from a standard chemical analysis of a rock, but nowadays he may also be interested in the possibility of having the so-called minor elements determined as well, for which purpose a spectrochemical analysis is frequently employed. Many petrologists are not, however, familiar with the geochemistries of the minor elements and are not likely to know, therefore, which of these rarer elements are likely to be present in quantities greater than merest traces, say 0.001–0.0001%; or if they are informed in this respect, they may not be acquainted with the spectral sensitivities of these elements. In any event, most petrologists submitting a rock specimen to a spectrochemist for a standard minor element analysis, are not likely to know what to expect from the analyst, nor what to ask of him, and this note has been prepared to aid them.

It is assumed that the spectrochemist has at his disposal a reasonably large spectrograph, because, as a result of the complexity of spectra emitted from rock specimens, an instrument of small dispersion would be capable of handling only a small number of elements. Further, if a microphotometer is available, a greater quantitative accuracy will be possible. Without this instrument, quantitative estimates are made visually and tend to be more semi-quantitative; however, if the petrologist is informed by the analyst that he has no microphotometer at his disposal, this should not make him feel suspicious of the results because experienced operators have practiced eyes and are capable of reporting reliable estimations, usually within ±30–40%.

Some laboratories may undertake some chemical pre-enrichment of the specimens prior to making a spectrochemical analysis. Such procedures involve working up of relatively large quantities of rock, and very many rare minor elements can

thereby be concentrated sufficiently to above their limits of spectral detection. This discussion does not include such procedures, because there is almost no limit to which such enrichment procedures can be carried, and the data are confined, therefore, to a so-called standard analysis, namely, an analysis of the rock as submitted. Two common rock types have been selected—a granite type and a diabase type—and the data given below may be regarded as typical of the minor elements that can be detected in the commoner silicate rock types, and also, as typical of the magnitudes of the quantities that are usually present. The data have been selected from several publications and are in part based on personal observations.

TABLE 1

Minor Constituents Which Can Usually Be Detected and Determined Spectrochemically

Element	(*a*) *Granite* %	(*b*) *Diabase* %
BeO	0.001	n.d.*
ZrO_2	0.1	0.003
La_2O_3	0.005	n.d.*
Y_2O_3	0.01	n.d.*
Nd_2O_3	0.003	n.d.*
BaO	0.2	0.005
SrO	0.05	0.10
Rb_2O	0.05	n.d.*
Cs_2O	0.002	n.d.*
Li_2O	0.01	0.002
Ga_2O_3	0.002	0.002
PbO	0.003	0.0004
NiO	0.0005	0.005
CoO	0.0005	0.004
Cr_2O_3	0.001	0.03
V_2O_3	0.0005	0.01
Sc_2O_3	0.001	0.003
CuO	0.005	0.01
GeO_2	0.0005?	n.d.*
Tl_2O	0.0003	n.d.*
Cb_2O_5?	0.01	n.d.*
Ag_2O	n.d.*	0.0002?
SnO_2	0.01	n.d.*
B_2O_3	0.0003	n.d.*
F	0.2	0.02

* Uusually not detectable.

If a procedure which utilizes an auxiliary furnace to distill off volatile elements into the source of excitation can be

employed as well, the following elements can also frequently be analyzed (Preuss, 1940): In, (Tl), Bi, Cd, Zn, Hg, Ge, Sn and Sb.

No two spectrochemists are likely to be in complete agreement about the elements they are capable of analyzing in common rock types, and in any case the facilities of no two laboratories are identical; consequently, the information given in table 1 is not to be taken very rigorously. Some operators may include a couple of extra elements, although this is unlikely, because the number of elements listed in table 1 can be regarded as approximately a maximum, and some may find it impossible to detect a few: it has to be borne in mind also that several of these elements occur as traces which border very closely on the limits of spectral sensitivity of detection, and, as a result, some discrepancies are not surprising. In the main, however, it is felt that these results may be taken as reasonably accurate, and the petrologist should be rather wary of accepting results which either include several extra elements, or exclude many that have been listed in table 1, unless a reasonable explanation is at hand. For example, a granite relatively rich in orthite will undoubtedly contain detectable quantities of many rare earth elements in addition to Y, La, and Nd, and the presence of orthite would of course be sufficient reason for expecting the detectable presence of such elements. As examples of the omission of elements, two examples are given: one analyst has reported the absence of scandium in certain ferro-magnesian minerals, and another, the absence ($< 0.001\%$) of gallium and rubidium in granite-like rocks. Scandium is normally ubiquitous in basic rocks and the surprising report of the first analyst has since been shown to be in error (0.009% Sc_2O_3 was found); likewise the absence of gallium and rubidium—both omnipresent in granite-like rocks—conflicts very sharply with what is known about the geochemistries of these two elements, and the latter analysis is thus suspect with respect to these two elements.

For a general quantitative analysis, it is not easy to state the accuracy with which each constituent will be reported. As already noted, a standard deviation of about ± 30–40% is to be expected where purely visual estimates have been made of line intensities, but if a microphotometer is available, standard

deviations are likely to range from ± 4.0–$\pm 30\%$: much will depend on the particular procedure employed, but a standard deviation of less than $\pm 4.0\%$ is very uncommon.

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REVIEWS

The Pulsation Theory of Variable Stars; by SVEIN ROSSELAND. Pp. vii, 152; 24 figs. Oxford, 1949 (Oxford University Press, $5.00).—The very active advances during recent years in the theoretical interpretation of stellar variability have hitherto been reported only in scattered form in the periodical literature. The need for a concise synthesis of this field has been well met by the present work by Professor Rosseland. He has done a valuable service to theoretical physicists and applied mathematicians in rendering accessible a subject containing many problems for their attack.

The author's theme is the theoretical investigation of the radial pulsations of gaseous stars. After a brief introductory account of stellar variability and a statement of the hydrodynamical principles involved, he summarizes investigations of the adiabatic oscillations of various stellar models with different degrees of central condensation. Next he considers non-adiabatic pulsations, and questions connected with the stability of stellar pulsations. A further chapter treats the famous "phase lag." Although a Cepheid variable which pulsates adiabatically should attain maximum brightness simultaneously with minimum radius, observation shows that greatest light actually occurs a quarter cycle later. No conclusive explanation is reached: the difficulty lies in the lack of observational tests to distinguish between alternative proposals.

Probably the most important section of the book is Chapter VII on anharmonic pulsations, which contains many new results of Rosseland. Here a qualitative explanation of the general asymmetry of Cepheid light curves is given, and hope is offered for the eventual detailed interpretation of the fine-structure of Cepheid light curves. This chapter summarizes the important investigations by Woltjer on the resonance interaction between different modes of pulsation. This work is an interesting application of the classical methods of celestial mechanics to a fresh field of usefulness.

The author now turns to relaxation oscillations of stars, which he applies to novae and to the SS Cygni-type variables, but with a brevity that will disappoint some readers.

An attractive feature of Rosseland's book is that, although his interests are chiefly theoretical, nevertheless his treatment maintains a close contact with the results of observation. The reader whose tastes are more largely observational may, however, wish that some topics less amenable to theoretical interpretation, such as Struve's spectroscopic observations of Cepheids, and the period variations of cluster type variables, could have been considered.

One correction of minor importance may be noted: on p. 42, the period of binary motion for S Sagittae should be 682 days and not 8.88; and Polaris deserves mention here as the best-studied case of a binary star system of which one member is a Cepheid.

Because of its technical character, the book is suited to the specialist, rather than to the general reader. It must be regarded as a very valuable contribution to astronomical literature.

JOSEPH ASHBROOK

Introduction to Statistical Mechanics; by G. S. RUSHBROOKE. Pp. xiii, 334. Oxford, 1949 (Oxford University Press, $4.25).—The purpose of this book, intended, as it is, for readers "who, while of limited mathematical experience, [i. e. calculus] require, nevertheless, to appreciate something of the content and importance of modern statistical theories, especially in the field of physical chemistry," invites a comparison with the recent work by Gurney (McGraw Hill, 1949) with the same title and aim. Although assuming approximately the same amount of mathematical knowledge, the two books differ considerably in their approaches. Gurney's treatment emphasizes the physical, intuitive presentation of familiar results, and pays relatively slight attention to the development of the reader's ability to cope with problems on his own. Rushbrooke, on the other hand, although covering more or less the same applications as Gurney, is primarily concerned with method, and with the development, at least in rudimentary form, of the various techniques which are applied in even the most difficult problems. To assist the reader in developing his mathematical technique, an excellent selection of problems is included after each chapter.

Although the fundamental concern of the book is with technique, the applications which have been chosen are generally of considerable practical importance, and include the development of the Einstein theory of specific heats, the Sakur-Tetrode equation, the thermodynamic properties of di- and polyatomic molecules, the law of mass action, the theory of phase transitions, the theory of the imperfect gas, and the theory of regular solutions. At the same time, he neglects such phenomena as Bose and Fermi statistics, which are of little interest to the physical chemist.

The development of the subject is based upon quantum mechanics, and the existence of discrete states. The results of classical statistical mechanics are obtained as the limits approached by the quantum mechanical formulae when the spacing of the states is very close. However, the reader who is willing to accept quantum mechanical results on faith will not feel handicapped by lack of previous acquaintance with the subject.

Perhaps the most outstanding feature of Rushbrooke's presentation is the clear analysis of the three major bridges between statistical mechanics and thermodynamics: the count of complexions, the partition function, and the grand partition function. These three major techniques are developed in a logical way which emphasizes the utility and limitations of each, and, while not becoming morbidly preoccupied with the minutiae of rigor, clearly distinguishes between the mathematical approximations and the physical hypotheses necessary in practical applications of statistics.

In summary, this book can be recommended as perhaps the best work available for the reader who really wishes to learn to understand and to use statistical mechanics.

HENRY C. THACHER, JR.

Chemismus und Konstitution; by BERND EISTERT. Stuttgart, 1948 (Ferdinand Enke Verlag, 39 German marks in paper, 41.50 German marks bound).—In this volume Professor Eistert has surveyed the dependence upon structure of the properties and behavior of chemical systems. This has involved an excursion, in somewhat rapid strides, through the realms of atomic physics, molecular spectra, dielectric behavior, chemical bond theory, general optical phenomena, thermodynamics, kinetics, acid-base theory, complexes and electronic mechanisms in organic chemistry.

Although the sequence of topics is excellent, and the general organization very thoughtful, the book is somewhat lacking in balance. The discussion of a few subjects, thermodynamics as an example, is brief to the point of being cryptic.

Since it is furnished with a bibliography which is complete and remarkably pertinent, this book should serve as an intelligent outline for a thorough study of all the material which it covers besides furnishing a very efficient introduction to most of the ideas presented.

P. A. LYONS

Subsurface Geologic Methods (A Symposium); compiled and edited by L. W. LEROY and HARRY M. CRAIN. Pp. 826, 487 figs., 33 tables. Colorado, 1949 (Department of Publication, Colorado School of Mines, Golden, $7.00).—Geologists and petroleum engineers will welcome this symposium, written by 41 experts, as a readable survey of most of the techniques now being used in exploratory subsurface work. The up-to-date discussions of subsurface laboratory methods touch on micropaleontology, detrital mineralogy, insoluble residues, thin sections, petrofabrics, screen and settling analyses, X-ray analysis, core analysis, and thermo-analysis. The reviewer finds the discussions of most of these methods lucid and

complete. However, more specific data seem desirable in the micropaleontology section on methods of recognizing and identifying important fossils that are valuable for age determinations and paleoecologic interpretations. Likewise, specific data on the microscopic recognition of various rocks and minerals would appear valuable.

Subsurface logging methods are treated thoroughly and special attention has been given to the various mechanical logging methods including electric, radioactive, caliper, temperature, spectrochemical. drilling time, and drilling mud analysis. The section on fluoroanalysis includes an explanation of the conventional fluorologging and fluorographic exploration, the latter of which is a fluoroanalysis of soil samples.

The chapter on miscellaneous subsurface methods should be particularly valuable to the geologists because it explains concisely methods of directional drilling, dip meter surveying, deep well camera, selective acidizing, various coring methods, core orientation, and the design and application of rock bits. In future editions the reviewer would desire brief explanations of drill stem testing techniques and gun perforating, both important items to the geologists. A non-technical discussion on mixing and maintaining drilling mud would also be helpful. It is suggested that the section on wax casts of pores in oil sands be expanded to include a discussion of plastic pore models of calcareous oil-bearing reservoirs. Further, it seems important to include a brief summary of the magnetic susceptibility method of separating granite wash from solid granite.

The chapter on subsurface graphic representation is important and it may do much to standardize map and log symbols, log colors, and log abbreviations. The selection of illustrations on how to show geological data is good. The suggestions on contouring should be read by every petroleum geologist. It would seem desirable to add a section here on how to make logs and maps for executive use.

A chapter on subsurface methods as applied to geophysics includes prospecting methods, basic principles, instruments, geological interpretations, and applications covering magnetic, gravity, seismic, and electrical methods. This should do much to aid co-ordination between geophysical and geological exploration.

Sections on subsurface methods as applied to mining and civil engineering work are short but complete. Finally, a chapter on sources of subsurface information describes various well sample libraries and services available in the Midcontinent and Rocky Mountain areas.

The reviewer believes that a brief selected list of references at the end of each unit of discussion would be valuable and an index

would add greatly to the usefulness of this very important symposium. SAMUEL P. ELLISON, JR.

Geology of the Southern Guadalupe Mountains, Texas; by PHILIP B. KING. U. S. Geological Survey Professional Paper 215, 1948, pp. vi, 183; 23 plates (18 of them folded, in pocket), 24 figs. (Government Printing Office, Washington, $3.25).—This is an outstanding publication based on thorough field study and mapping, by a geologist who had the large advantage of extended acquaintance with the general region. More than 20 years ago he began studies that led to description and interpretation of exceptionally interesting stratigraphy and structure in the Glass Mountains, the Marathon Basin, and other parts of the trans-Pecos region in western Texas. The present study of a critical area underlain by Permian rocks is of great value not only to geologists interested in problems of the immediate area, but also to students of geologic principles. In particular, any presentation of the principles of stratigraphy will find rich source material in this publication.

Sedimentary rocks described and interpreted in the report were formed in and adjoining a structural basin of Permian time. Sand deposits in the basin merged and intertongued with calcareous deposits on a shelf area to the north. Near the margin of the shelf great reef deposits were built up; the thickest of these, the Capitan limestone, nearly 2000 feet thick, forms the abrupt cliffs of El Capitan and Guadalupe Peak. This great mass changes laterally, within astonishingly short distances, into less resistant deposits that were contemporaneous with the reef. Probably nowhere in the world are there finer examples of facies changes in ancient sedimentary formations. Relations between intergrading and intertonguing rock types appear with diagrammatic clarity.

Abundant invertebrate fossils in the formations also present a valuable study of facies. Lateral faunal changes reflect differences in environment; vertical changes indicate both changing environments and progressive evolution of the organisms. Thus the biostratigrapher has an unrivalled opportunity to combine studies of biofacies and lithofacies.

The Guadalupe Mountains have a gradual slope eastward, with exterior drainage. On the west, descent is abrupt to an interior basin. Since the western front is marked by northwesterly faults of large aggregate throw, the mountain unit is a typical fault block, at the extreme eastern edge of the Basin and Range province. Several sets of faults make a remarkable pattern. The author also took observations on hundreds of joints, which in general conform to the pattern of faults. No doubt interpretations of these fractures by students of tectonics will differ; but it is

important that the basic data are recorded on a chart, with additional information in the text. Thus students of tectonics also will find valuable source material in the report.

Considerable space is devoted to description of land forms and related sedimentary deposits. An unusual and welcome feature of the peper is inclusion of five large folding plates, each depicting panoramic views in sketches made by the author. These excellent sketches give the reader a vivid appreciation of the principal topographic features of the area, and in a marked degree of the relation between these features and the bedrock geology.

CHESTER R. LONGWELL

The Ellenburger Group of Central Texas; by PRESTON E. CLOUD, JR., and VIRGIL E. BARNES. The University of Texas Publication No. 4621. Pp. 474; pls. 45, figs. 8. Austin, 1948 (Bureau of Economic Geology, paper bound $5.00, cloth $6.00).—The present report is the result of an extensive survey of the 800 to 1,800 feet of Lower Ordovician limestone and dolomite that crops out in the Llano uplift or Central Mineral region of Texas. The work was carried out cooperatively by the Texas Bureau of Economic Geology and the United States Geological Survey, and the immediate purpose of the survey was to obtain information on possibilities for petroleum in the adjacent subsurface. Those who directed the work wisely insisted however that the study be extended to every aspect of the Ellenburger rocks and to the subjacent and superjacent formations, and the authors carried this program out with tenacious thoroughness. As a result, the report presents not merely conclusions on the economic possibilities, though these are not neglected, but also a great fund of basic scientific information on the Ellenburger, and it will be a fundamental reference for years to come.

But the value and interest of the report will not be confined to those interested in the Ellenburger group in surface and subsurface. The survey raised several of the basic problems of the carbonate rocks, and the authors did not shirk the task confronting them. The 80-page section entitled "Lithogenic and paleoecologic speculations" contains, beside speculation, much pertinent fact and soundly reasoned inference. Another outstanding section is the "Glossary of selected technical terms," which is an important contribution to the vexed problem of the field description and classification of carbonate rocks. Indeed one of the excellent features of the report is the care and precision exhibited in the use of the terminology adopted. In places this terminology produces cumbersome writing, but the advantage of precision outweighs that defect. These two sections alone make the report a major contribution to sedimentary petrology.

A notice of the book would be incomplete without mention of the illustrations. Twelve of the plates are geologic maps of various key areas, and 28 are large collotype plates, including ground photographs, stereopairs from air photographs, and plates of typical fossils. The reproduction leaves nothing to be desired—except more plates. With this publication the state of Texas has set a new high standard for geologic reports, as to both form and content.

JOHN RODGERS

L'Eodevonien de l'Ardenne et des Regions voisines; by E. ASSELBERGHS. Mem. Inst. geol., Univ. Louvain. Vol. 14, pp. 1-598, 10 plates, 121 text figs., 1 large map in color. Louvain, 1946.—This imposing volume is the summation of more than 20 years of work during which time Professor Asselberghs has made a regional study, in great detail, of the Lower Devonian formations as exposed in and about the Ardenne Range of Belgium and northern France.

In this region the Lower Devonian varies in thickness from about 9,000 to over 14,000 feet. All stratigraphic units are described in detail, correlations throughout the region are presented, and regional variations in thickness and related changes in facies are described. Faunas are listed, but fossils are not illustrated or described since the species are already so well known through the work of Mailleux.

American stratigraphers will be interested to note that although the Ardennes are near the classical region of Coblenz, the author follows Gosselet in replacing the well-known Coblenzian stage by two stages. Thus the Lower Devonian is divided into three stages, the Gedinnian, the Siegenian, and the Emsian, listed in ascending order.

A large map in color, on a scale of $\frac{1}{200,000}$, enables the reader to follow the detail with ease, and facies changes, thickness, and structure are all effectively illustrated in the large fold-in plates. Dr. Asselberghs has produced a magnificent summary of a classical region of Devonian stratigraphy.

CARL O. DUNBAR

ERRATA

Through an unfortunate oversight, a halftone illustration was omitted from many copies of the January issue of the JOURNAL when it was bound. This is figure 2 in the article by Ralph E. Digman entitled "An exposure of the Triassic eastern border fault in Connecticut." The printer has mailed to each subscriber a copy of the halftone.

G. L. Davis and H. H. Hess, vol. 247, p. 868, Table 6. First line should read ADDIE Dunite P-391.

American Journal of Science

MARCH 1950

STRUCTURE AND ORIGIN OF TWO WINDOWS EXPOSED ON THE NITTANY ARCH AT BIRMINGHAM, PENNSYLVANIA

HAROLD D. FOX

ABSTRACT. There are two windows located on the axis of the southern end of the Nittany arch of central Pennsylvania. The windows are named the Birmingham window and the Knarr window.

The formations exposed within the windows are overturned, and have been graben faulted. The thrust which bounds the greater part of these two windows is low angle only within the area of the windows, and terminates very rapidly southwest of the windows.

The present interpretation of the structure of the windows differs from former interpretations. It is believed that local synclinal folding and faulting were the major factors in the development of the present structure. This was later covered by a thrust of relatively small stratigraphic displacement.

INTRODUCTION

IN the area surrounding the town of Birmingham, Pennsylvania, and along the Birmingham fault, two unusual windows (fensters) are exposed. Birmingham is located within the Tyrone quadrangle of central Pennsylvania, two and one-half miles southeast of Tyrone.

The region mapped is twenty-four miles long and an average of three and one-half miles wide. The location of the area and the surrounding topographic quadrangles are shown in figure 1.

The first geological work in this region was undertaken in the summer of 1841 by Harvey B. Hall, an assistant geologist of the First Pennsylvania Survey. In the summary report of the first survey H. D. Rogers (1858, pp. 503-504) included a section along the Little Juniata River from Union Furnace northwest to the town of Birmingham. It was in this report that the presence of a fault at Birmingham was first noted.

In 1881 Franklin Platt (1881) published a report of the geology of Blair County, and in 1885 J. P. Lesley (1885) published a report on Huntingdon County. These reports represented the work of the Second Pennsylvania Survey. It was

the opinion of these men that there was no major faulting at Birmingham.

No further work was done until the first decade of the twentieth century when Charles Butts mapped the Tyrone quadrangle. He realized for the first time that the rocks exposed

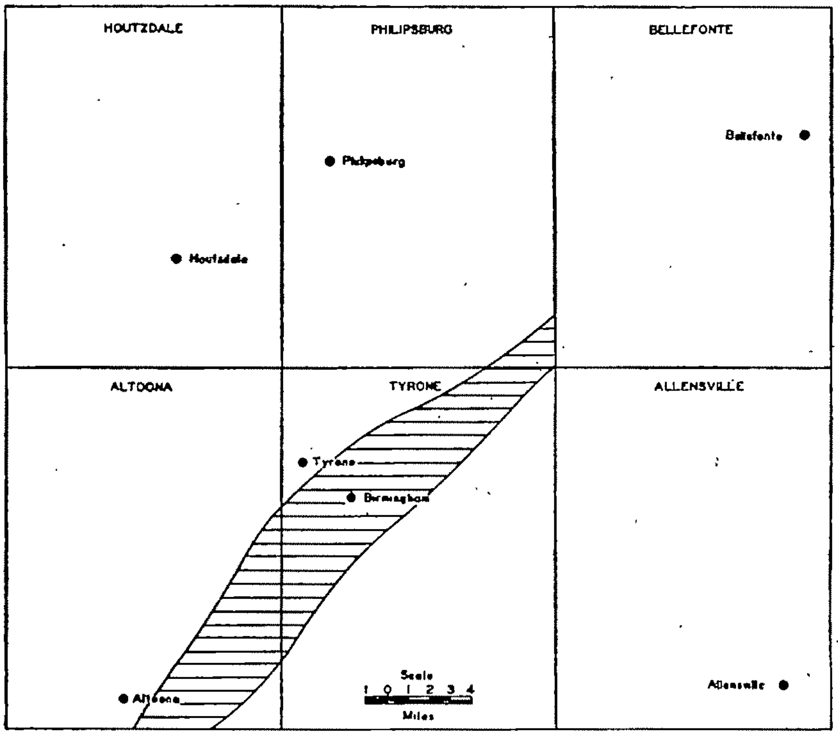

Figure 1. Area mapped (lined) in relationship to the 15′ quadrangles of central Pennsylvania.

at Birmingham were not of Cambrian age, but rather represented the Carlim- Tuscarora sequence of the upper Ordovician and lower Silurian. He (Butts, 1918) further noted that the beds at Birmingham were overturned.

It was not until Butts (1939) published his Tyrone quadrangle report that a second window, two miles northeast of Birmingham, was mentioned.

In the summer of 1947 the writer spent one week on reconnaissance of the general geology of the Birmingham region; and in the summer of 1948 eight weeks were spent in the field. Topographic maps were used as a base for mapping the area outside the two windows; but within the windows it was neces-

sary to use a base map of a larger scale. For detailed mapping, aerial photographs on scales of one to sixteen hundred and sixty-seven and one to one thousand were used.

It is interesting to note that no windows, except the two in the Birmingham area, have been reported in the northern section of the folded Appalachian province.

STRATIGRAPHY

The first detailed stratigraphic section of the formations mapped in the Tyrone quadrangle was published by Butts (1918). This was revised in his paper on the Tyrone quadrangle (1939). Later, G. M. Kay (1944) published the results of a detailed study of the middle Ordovician of central Pennsylvania. The detailed description of the formations of these groups will not be repeated here as it is covered in the papers mentioned above.

The Chazy and Black River are undistinguishable within the windows as these beds are brecciated to such an extent that only the gross lithologic relationships can be determined. It is possible to distinguish the Trenton from the Chazy and Black River, because the Trenton is darker and thinner. The basic difference between the two sections of Butts and Kay is the position of the boundary lines (Table 1), which was largely determined by the fauna. In working out the structure of the southern end of the Nittany arch these

TABLE 1

Comparison of published sections of Chazy, Black River, and Trenton stages.

Butts (1939)			Kay (1944)		
Formation	Thickness (in feet)	Stage	Formation	Thickness (in feet)	Stage
Reedsville	1100	Eden	Reedsville	——	Eden
			Antes	400	Trenton
Trenton	500	Trenton	Coburn	300	
			Salona	200	
Rodman	30	Black River	Nealmont	150	
Lowville	337		Curtin	140	Black River
			Benner	40-200	
Carlim	250	Chazy	Hatter	70-110	Chazy
			Loysburg	50-80	

differences are negligible. It was found expedient, therefore, to follow Butts' classification since his formation names are used on the only published areal geological map of the Tyrone quadrangle.

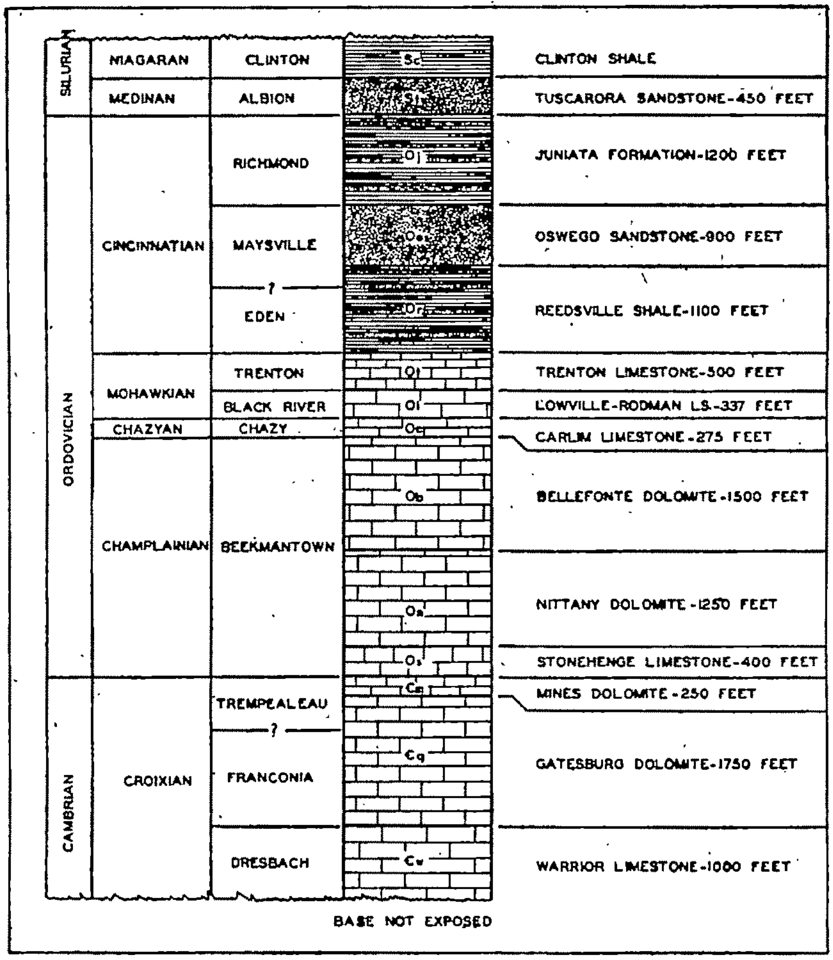

Figure 2. Stratigraphic section of rocks exposed on the south end of the Nittany arch (modified after Butts, 1938).

Figure 2 is a stratigraphic section of the formations as mapped in this paper.

STRUCTURE

The Nittany Arch. The last great westward structure of the folded Appalachians is the Nittany arch. To the north-

west are the minor folds of the Allegheny plateau; and southeastward the folded Appalachians extend for fifty-three miles to the Piedmont Province. This arch, which really is an anticlinorium, extends from Altoona to Muncy, ten miles east of Williamsport, a distance of 110 miles. Across the strike it reaches from the Allegheny escarpment, northwest of Tyrone, to the Broad Top syncline southeast of Huntingdon, thus having a minimum width of twenty-six miles.

The Nittany arch has a consistent northeast-southwest strike throughout its length. Where the arch dies out by plunging to the northeast, the trend of the Appalachian folding swings through a major change of some 40° to the east. The plunging to he northeast, the trend of the Appalachian folding the Sinking Valley anticline (fig. 3). The axis may be considered to extend from north of Warriorsmark to seven miles south of Altoona, a distance of more than twenty-five miles. This anticline is asymmetrical, dips on the southeast flank averaging 25° to 35°, whereas the beds on the northwest flank are at first overturned to the southeast, then vertical, and gradually flatten out to the northwest. Along the Allegheny escarpment the dips are 15° or less to the northwest.

The Birmingham Fault. The south end of the Nittany arch is broken by the Birmingham fault. This fault lies along the axis of the arch, extending from one mile northeast of Culp to four miles southwest of Bellefonte, a distance of some thirty miles. Figure 3 shows the southern nineteen miles of this fault.

From the vicinity of Warriorsmark northward it appears to be a fairly high angle fault. Although no dip was obtained in the field, the trace of the fault plane through irregular topography indicates that it dips 40° to 50° to the southeast. North of Warriorsmark, where the upper Warrior limestone is thrust against the Stonehenge, the stratigraphic throw is about 1800 feet. At Stormstown, more than eight miles farther northeast, where the upper Warrior is thrust against the lower Nittany dolomite, the stratigraphic throw is about 2000 feet.

In the vicinity of Birmingham the fault is folded, as shown by the windows, and the dip is much lower and variable. At Birmingham the fault is exposed along a railroad cut (pl. 1, fig. 1). The local dip at this exposure is 15° to the southeast.

The fault here forms the southeast frame of the Birmingham window, and the stratigraphic throw is a minimum of 5000 feet. One and one-half miles southwest of Birmingham the Stonehenge is thrust over the lower Nittany, and the stratigraphic throw is less than 1000 feet. Beyond this point the throw decreases rapidly, and five miles south of Birmingham the fault is no longer evident.

The Birmingham Window. Along the top of the Nittany arch, an area of overturned formations at Birmingham was described by Butts (1939), and it is here named the Birmingham window. This window is about one mile long and half a mile wide (fig. 4). It is surrounded by the Gatesburg dolomite except for about 2000 feet along the northwest edge, where the Stonehenge limestone and the Nittany dolomite form the boundary.

A section along the main highway from southeast to northwest begins just southeast of the axis of the arch in the Gatesburg dolomite, which is dipping 10° to the southeast (fig. 5), section A-A^1, and fig. 4). Here the Birmingham fault (fault 4, figs. 4 and 5) has thrust the Gatesburg dolomite over the Carlim limestone, and forms the south frame of the window. The Carlim is then exposed for 1200 feet. Since it is impossible to distinguish between the Carlim, Lowville and Rodman, because of folding and shattering, all the massive limestone within the window is mapped as Carlim. The Carlim-Trenton contact appears to be normal, although the beds are upside down with the Carlim lying above the Trenton. The Trenton has been highly folded, and it is impossible to obtain a dip that has much significance throughout the 250 feet which it covers. At the most, only 125 feet of the original 500 feet of the Trenton is present. The contact between the Trenton and the Oswego sandstone is a fault contact. This fault (fault 3, figs. 4 and 5) has cut out the remaining Trenton, the Reedsville shale, and part of the Oswego: thus having a minimum stratigraphic throw of 1750 feet. There is 200 feet of Oswego sandstone exposed dipping about 45° to the southeast; thus only 140 feet of the normal thickness of 900 feet of the Oswego is present. The last twenty feet of Oswego is covered, but the contact between the Oswego and the Juniata formation must be assumed to be a fault (fault 2a, figs. 4 and 5) as the normal thickness of the Juniata is

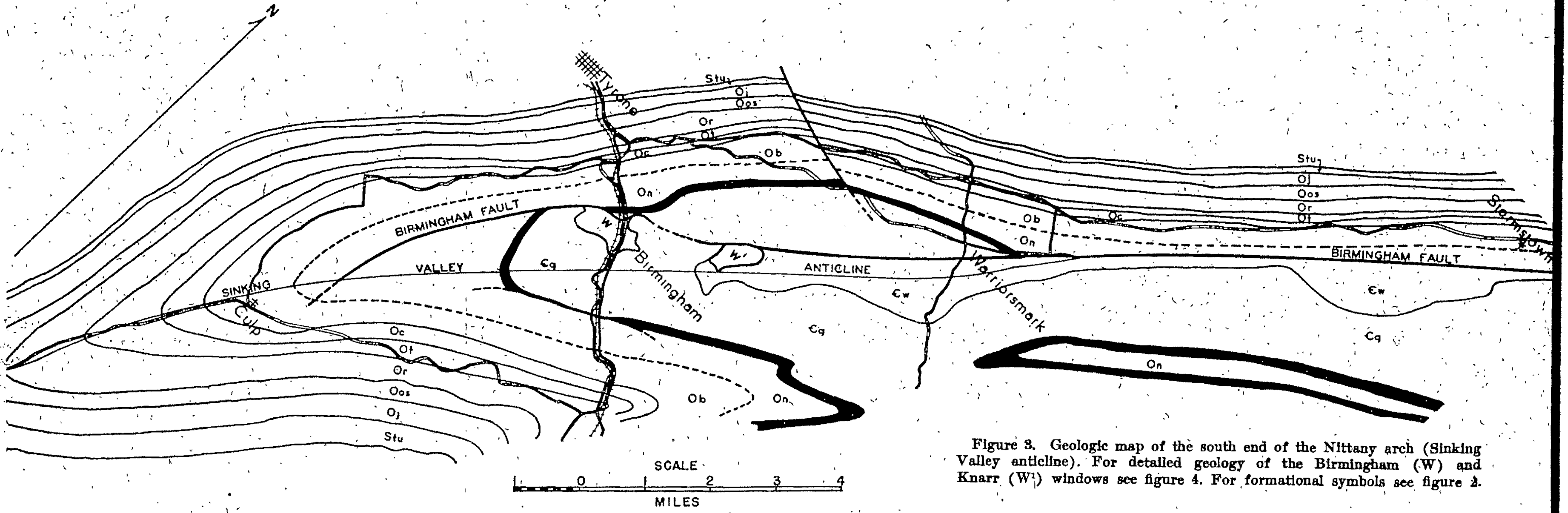

Figure 3. Geologic map of the south end of the Nittany arch (Sinking Valley anticline). For detailed geology of the Birmingham (W) and Knarr (W^1) windows see figure 4. For formational symbols see figure 2.

Excavations in Northeastern Massachusetts; by Ripley P. Bullen. Papers of the Robert S. Peabody Foundation for Archaeology, vol. 1, no. 3. Andover, Mass., 1949.

The Boylston Street Fishweir II; by E. S. Barghoorn, P. S. Conger, Sheldon Judson, F. B. Phleger, and L. R. Wilson. Frederick Johnson, Editor. Papers of the Robert S. Peabody Foundation for Archaeology, vol. 4, no. 1. Andover, Mass., 1949.

Some Tertiary Mammals and Birds from North America; by R. W. Wilson, Hildegarde Howard, Loye Miller, and Chester Stock. Carnegie Institution of Washington Publication 584, Washington, D. C., 1949 ($3.75 in paper cover; $4.25 in cloth binding).

Stratigraphy and Petrology of Buck Hill Quadrangle, Texas; by S. S. Goldich and M. A. Elms. Report of Investigations No. 6, Bureau of Economic Geology, University of Texas. Reprinted from Bull. Geol. Soc. America, vol. 60, no. 7, July, 1949 (50c in paper cover).

Third Symposium on Combustion and Flame Explosion Phenomena; by Standing Committee on Combustion Symposia. Baltimore, 1949 (The Williams and Wilkins Company, $13.50).

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Modern Breeds of Livestock; by H. M. Briggs. New York, 1949 (The Macmillan Company, $5.50).

Introduction to Theoretical and Experimental Optics; by Joseph Valasek. New York, 1949 (John Wiley & Sons, Inc., $6.50).

Some Recent Researches in Solar Physics; by F. Hoyle. New York, 1949 (Cambridge University Press, $3.00).

Principles of Field Crop Production; by John H. Martin and Warren H. Leonard. New York, 1949 (The Macmillan Company, $6.00).

Quantitative Chemical Analysis; by George L. Clark, Leonard K. Nash, and Robert B. Fischer. Philadelphia, 1949 (W. B. Saunders Company, $4.25).

Principles of Organic Chemistry; by John L. Abernethy. Philadelphia, 1949 (W. B. Saunders Company, $4.00).

Scientific Autobiography and Other Papers; by Max Planck. New York, 1949 (Philosophical Library, $3.75).

ERRATA

In the article by F. Chayes "On a Distinction Between Late-Magmatic and Post-Magmatic Replacement Reactions," printed in the January issue, page 27, equation (4) should read

$$r_{13} = \frac{s_1 + r_{12}s_2}{\sqrt{(s_1^2 + s_2^2 + 2r_{12}s_1s_2)}}$$

and page 29, equation in the middle of the page should read

$$r_{13} = \frac{s_1}{\sqrt{(s_1^2 + s_2^2)}}$$

trates how far American stratigraphy has come in the last two decades.

Two unfortunate defects mar the work. Firstly, the same geographic name is used in a few cases both for a formation and for a member of that formation, in violation of the accepted rules of American stratigraphic nomenclature (Committee on Stratigraphic Nomenclature, 1933, Art. 7, remark f; Art. 11, remark c). These duplications could easily be avoided by using lithologic instead of geographic terms for the members in question. Secondly, throughout the work the names of fossils are given without the name of the original describer. In general it is unfortunate that Wilson, who quite properly checked every aspect of the physical stratigraphy in the field, has accepted much of the paleontology at second hand.

The outstanding contribution made by this report is therefore in physical stratigraphy, particularly in the recognition of the complex facies relationships in the upper Middle Ordovician Nashville group ("Trenton" of previous reports). Inasmuch as these rocks are relatively fossiliferous, the way is now open for some fascinating studies on the control of fossil faunas by depositional environment.

References: Bassler, R. S., 1932. The stratigraphy of the central basin of Tennessee: Tennessee Div. Geology, Bull. 38.

Committee on Stratigraphic Nomenclature, 1933. Classification and nomenclature of rock units: Geol. Soc. America Bull., vol. 44, pp. 423-459.

JOHN RODGERS

PUBLICATIONS RECENTLY RECEIVED

Applied Experimental Psychology; by A. Chapanis, W. R. Garner, and C. T. Morgan. New York, 1949 (John Wiley & Sons, Inc., $4.50).

Handbook of South American Indians; Julian H. Steward, Editor. Volume 5. The Comparative Ethnology of South American Indians. Bureau of American Ethnology Bulletin 143. Washington, D. C., 1949 (U. S. Government Printing Office, $3.00).

Theory of Hearing; by E. G. Wever. New York, 1949 (John Wiley & Sons, Inc., $6.00).

Acoustic Measurements; by Leo L. Beranek. New York, 1949 (John Wiley & Sons, Inc., $7.00).

Applied Silviculture in the United States; by R. H. Westveld. New York, 1949 (John Wiley & Sons, Inc., $6.00).

Annual Reports on the Progress of Chemistry for 1948, vol. 45. London, 1949 (The Chemical Society, £1/5/0).

The Elements of Genetics; by C. D. Darlington and K. Mather. New York, 1949 (The Macmillan Company, $3.75).

The Geology of Pietermaritzburg and Environs; by Lester C. King. Pretoria, Union of South Africa, 1949 (Dept. of Mines, Geological Survey, 5s. (including Map)).

tribution of the sediments now accumulating on it, the volcanic activity so prominent in the area, the stratigraphic and structural history revealed by the rocks, and the seismic and gravimetric data available—and proceeds to a carefully considered and attractive synthesis. Moreover it is beautifully prepared and well and lavishly illustrated, though readers would be well advised to provide themselves beforehand with a fairly detailed map of the archipelago.

In short, the book might be considered the geological equivalent of "light" reading, and it provides a brief but unhurried survey of an area of great interest by a master in its geology. From his own experience, the reviewer believes that few geologists will want to put the book down before they have finished the last paragraph. JOHN RODGERS

Pre-Chattanooga Stratigraphy in Central Tennessee; by CHARLES W. WILSON, JR. Tennessee Division of Geology Bulletin 56. Pp. xviii, 408; 28 pls., 89 figs. Nashville, 1949.—Wilson's report is an exhaustive account of the physical stratigraphy of the Ordovician, Silurian, and Lower and Middle Devonian rocks exposed on the Nashville dome and in the Western Valley of the Tennessee River. It is based on mapping of the formations in question and on the measurement of approximately 700 stratigraphic sections. The maps are not included in the report, but they will be released separately by the Tennessee Division of Geology (scale: 2 miles to the inch). Thirty cross-sections, built up of 5 to 21 individual sections each, present the stratigraphic details, which are generalized in several stratigraphic diagrams and 38 isopach maps of various formations and members. There emerges a clear and authoritative picture of the geological history recorded in the rocks. In particular, Wilson's precise data clarify the history of the Nashville dome as a positive area, and he shows how as an island or shoal it influenced the distribution of facies at several times, beginning in the Middle Ordovician.

As a definitive work on the area, the report inevitably invites comparison with the earlier report by Bassler (1932). The differences in interpretation between the two reports are great, and they stem largely from fundamental difference in the approach to correlation. Bassler adhered to the view of E. O. Ulrich that two bodies of rock having different lithology and different fossils are the deposits of separate embayments of the sea and are therefore distinct formations of different ages. Wilson is steeped in modern ideas of facies change, and he recognizes as many as six different roughly contemporaneous facies in certain formations. The change illus-

Effects of Irrigation on Soil Characteristics; Drainage; Reclamation and Management of Saline and Alkali Soils; and Control of the Physical Properties of Soil.

Particularly helpful to those not specially familiar with soil terminology is the inclusion of a Glossary. Some of the terms used are new and have not yet been established in the literature. It may be premature to include them for their definition may change with usage. An Appendix is also included giving information useful in soils work.

A Bibliography is included at the end of each chapter. Reference is not made to all of the references in the text which tends to lessen the usefulness of the Bibliography.

The book could have been improved by including a chapter on the basic nature of soils, as, for example, description of a soil profile. It would also have been helpful to have included morphological descriptions of soil structure in arid regions in more detail since the natural structure of soils in those regions exert such a profound influence on their use.

The book is well printed and well illustrated; especially good are the diagrams and graphs showing moisture relationships in soils.

C. L. W. SWANSON

Structural History of the East Indies; by J. H. F. UMBROVE. Pp. xii, 64 (quarto); pls. 10, figs. 68. London and New York, 1949 (Cambridge University Press, $4.00).—This is a refreshing book. Based on a series of lectures given at Cambridge in 1946, it is informal in tone and disarmingly undogmatic in argument. It ends with a statement of the vastness of our ignorance and a frank admission that the working hypothesis so lovingly erected is certain "to be discarded as soon as new facts are revealed." Yet there is a dramatic quality in its plan, which begins with a quiet discussion of drowned rivers and coral reefs, builds up subject after subject to the brink of an explanation, and finally ties all threads together in the final chapter.

To be sure, the book does not contain much that is not already in the literature and will not become an indispensible reference work for future investigators. The factual documentation and the chains of argument are too incomplete for that and the bibliography also is short and weighted somewhat in favor of review articles. But exhaustive discussion was not its intent, and the book does present a stimulating review of all the different lines of evidence that must go into a reconstruction of the tectonic history of the East Indies—the configuration of the sea floor and the dis-

REVIEWS

Fluid Dynamics; by VICTOR L. STREETER. Pp. xi, 263, New York, 1948 (McGraw-Hill Book Co., Inc., $5.00).—This is a textbook for use in a senior or graduate course in fluid mechanics. The material is well arranged, and great care has been taken to present all mathematical detail needed for an understanding of this very analytic subject. Proofs tend to be lengthy and little is left to the reader, all of which gives the book a wholesome measure of teachability and places its contents well within the grasp of a student who has had a course in the calculus. An awkward prose, a profusion of dangling participles make the text material at times a bit obscure, but equations and diagrams always shed sufficient illumination to sustain the reader.

The plan of the book is well described by the publisher, who notes on its fly leaf:

"This book first formulates the basic ideal fluid theory, followed by examples of three-dimensional flow. Then, the necessary concepts in complex variables are introduced, so that all two-dimensional flow cases may be approached from the viewpoint of conformal mapping. Free streamlines are introduced with several examples of their use. Vortex theory is then developed, with two- and three-dimensional examples. The Navier-Stokes equations are derived and applied to several flow problems, including the laminar boundary layer."

HENRY MARGENAU

Irrigated Soils; Their Fertility and Management; by D. W. THORNE and H. B. PETERSON. Pp. ix, 288; 74 figs. Philadelphia and Toronto, 1949 (The Blakiston Company, $5.00).—This new book on the management of irrigated soils should be useful to everyone interested in water movements in the soil profile and their relation to crop production, engineering, geology, and the like. It is the only one of its kind available, as most books on soils deal with their use and management for crop production in humid areas. The management of soils in arid regions is given special emphasis.

New concepts of soil moisture are presented clearly and are illustrated unusually well with diagrams. The book also discusses relationships between organic matter, microbiology, fertilizers, and their use as ordinarily covered in general texts on soils. Other chapters of special interest, out of the 25 included in the book, are Soil, Water, and Plant Relations; Plant Relations to Saline and Alkali Soils; Evaluating Land for Irrigation; Measuring Irrigation Water; Field Application of Water; Irrigation Practices for Various Crops;

half of its original size. This is consistent with the statement of Mr. Bonafede that the stone originally weighed about 4 kg., and with the statement of Buchner that there was a stone of 3 to 4 kg.

The larger stone has been given by the writer to the United States National Museum, the smaller to the Chicago Natural Museum.

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Vom Rath, G., 1869. Über den Meteoriten von Girgenti: Pogg. Ann., vol. 138, pp. 541-545.

Wülfing, E. A., 1897. Die Meteoriten in Sammlungen.

Adrian, Michigan

Thus the weight of all known fragments is increased to 3,574, which added to the 10,901 grams of the two masses, gives 14,475 grams as the total known weight.

Girgenti is a typical white veined chondrite, the accompanying illustrations showing the characteristic veining and fusion crust. The photographs were taken of the smaller mass because it shows the veining more distinctly than the broken surface of the larger one.

The large stone is somewhat quadrangular. It is about 25 cm. long, 15 cm. high and 15 cm. thick, treating the flattest side (about 23 x 13 cm.) as the base of the mass. This base is crusted, and there are remnants of crust on the top.

The crusted surface of the base is quite flat and even, the depressions being too small and numerous to be properly described as thumb marks. One side, about 20 x 10 cm., bears a well-preserved crusted area about 5 x 10 cm. which shows characteristic thumb marks, and the same is true of remnants of the crust on the top, and of an area about 7 x 12 cm. on one end of the mass.

One side presents a fairly even broken surface about 23 x 12 cm., which is slightly darkened to a general brownish shade. This darkening does not suggest an incipient crusting or "scorching" during flight; it is likely that in the course of almost a century oxidation has made brownish spots around the minute and thickly dispersed grains of nickel-iron.

The top presents a broken surface about 18 x 7 cm. which appears fresher than the one just referred to, it being light gray with no spots of oxide. This surface shows distinctly the veins, a number of which are traceable for 18 or 20 cm. across the top and down the broken side.

The smaller mass is very similar to the larger. It has rounded outlines, though somewhat quadrangular in its general shape. It is about 13 cm. long, 11 cm. wide and 10 cm. high, considering the flattest side as the base of the mass. The base, one side and the top are covered with a perfect and fresh-looking crust. The side and top are strongly thumb-marked; the basal surface, which is quite even, shows only small depressions.

One side and both ends show fresh-looking broken surfaces on which the numerous veins are conspicuous. From the general shape and curvature, the mass may be approximately

Rath mentioned the existence of a second stone—the "pietra entera"—its location was apparently unknown at that time. It could not have been in the possession of Salvatore Bonafede, so evidently Lo Giudice gave it to him subsequently. This must have been considerably later, because in his letter at least fifteen years after the fall Gemmellaro had no definite knowledge of the second stone. This stone, we may conclude, is the "pietra entera," which until now remained unknown to scientific writers.

The smaller stone seems to be about half of its original mass, and the portions broken away probably account for most of the fragments listed by Wülfing. It seemed a natural supposition that the fragments were broken off by Gemmellaro, but Mr. Bonafede states that they were broken off and distributed by his uncle, the professor having had the stone merely as a loan. He states that the original weight (as recalled by his uncle) was about 4 kg. If so, some of the 3,389 grams listed by Wülfing must have come from other sources, perhaps fragments found on the Lo Giudice farm.

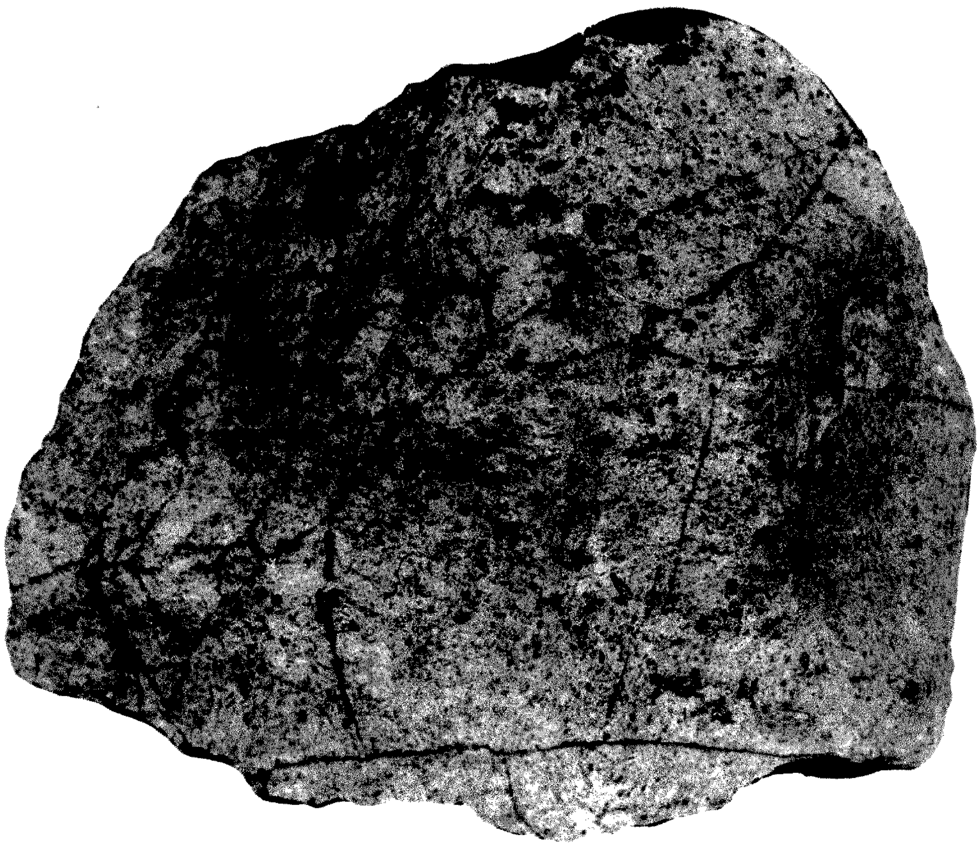
Of the 3,389 grams in Wülfing's list 2,792 were in six collections—Rome 1,104, Berlin 489, Paris 474, Turin 184, London 246, Pohl 208. The remaining 597 grams of fragments, from 87 grams down to one, were scattered in 22 collections—all European except Harvard 20 grams, Bement 1, and Washington 1. As late as 1912 Foote in his list of meteorite values considered Girgenti such a rarity that he gave it a value of $2.07 a gram.

The distribution as given by Wülfing probably has not materially changed, though London now has 120 grams more, Paris 107 less, and available catalogues give Chicago 85 grams, New York 8.9, Prague 14 and Greifswald 4. There likely has been some redistribution of the 263 grams in private collections included in Wülfing's total.

After acquiring the two main masses, the writer obtained 185 grams of fragments—seven weighing 93 grams from Mr. Bonafede who got them from Giuseppe Lajacarno of Agrigento, and 92 grams from the collection of Professor Meli of Rome.

PLATE 2

Broken surface of the smaller Girgenti stone showing veins. (The photo is larger than natural size, which is 11 cm. wide and 10 cm. high.)



more abundantly than the iron; it is bronze-yellow to tomback brown in color, occasionally running into steel blue."

A further discussion of the components is followed by analyses showing 8.3% of nickel iron in the mass, the composition of which is given as 87.3 Fe and 12.7 Ni, and by analyses of the non-metallic portion.

The uncertainty regarding the "two stones" now apparently is cleared up. In 1948 through correspondence with Giuseppe Bonafede of Palermo, a collector of minerals and fossils, the writer learned that he had the two masses and obtained them from him, together with their history.

The fall, according to Mr. Bonafede, was on a farm near Girgenti then owned by Gaspare Lo Giudice. It took place during a storm, accompanied by a flash of light and the characteristic noise, alarming the farm workmen. Several of them found a heavy stone that had fallen and brought it to Mr. Lo Giudice, who gave it to his friend Salvatore Bonafede of Palermo, an amateur student of rocks and minerals and an uncle of Giuseppe Bonafede.

Subsequently Lo Giudice gave him a second stone, presumably one that he had kept from the time of the fall. Giuseppe Bonafede inherited both in 1909 when the uncle died at the age of 70 years.

Which of these stones was the one of 3 to 4 kg. mentioned by Buchner, and which was the "pietra entera" referred to indefinitely by Gemmellaro in his letter to Vom Rath?

Mr. Bonafede states that when his uncle first received a stone from Lo Giudice he lent it to Prof. Gemmellaro for study. The latter, whose full name was Gaetano Giorgio Gemmellaro, was a professor of Geology in the University of Palermo, where a street still bears his name. He was a close friend of Salvatore Bonafede, but did not know Lo Giudice.

The fact that he borrowed the stone for study would indicate that it was a new meteorite, the first recovered. That also may be inferred from the fact that Salvatore Bonafede broke off and sold fragments of it after Gemmellaro had returned it to him. Though Gemmellaro in his letter to Vom

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PLATE 1

The smaller (2,151 gr) Girgenti stone showing fusion crust. (The photo is slightly larger than natural size, which is 13 cm. in length.)

cipal mass has remained in the possession of Prof. Gemmellaro, now in Palermo. Regarding the stone itself Buchner says it is 'dense, fine-grained, and includes fine silver-white iron particles.'

"Since Dr. Krantz has not only placed at my disposal for study the two larger pieces of stone lately brought from Palermo (16.602 gr and 38.439 gr in weight), but also gave me several smaller fragments for analysis, I very gratefully avail myself of the opportunity to contribute something to the knowledge of that rare stone.

"Unfortunately my wish to learn something of the circumstances of the fall was not fulfilled. Mr. Gemmellaro at my request interviewed several persons in Girgenti, but no one could be found who was an eye-witness of the occurrence, or who could give any reliable information about it. It is one of the many meteoric falls of which the phenomena are wholly lost to science.

"The supposition that only one stone fell at Girgenti seems to be erroneous according to the statement of Gemmellaro in a letter, who mentions in addition to the one in his possession still another 'whole stone' (pietra entera) belonging to the same fall. Gemmellaro's stone is, except for the pieces broken off, fully crusted. The two pieces submitted to me are partly covered with a black fusion crust. It is somewhat wavy and shows small prominences which betray the presence of nickel-iron. The stone is a chondrite, light grayish-white, very fine-grained, appearing almost homogeneous to the eye.

"On a broken surface appear a multitude of very fine fusion lines. They run from the outer fusion crust, and appear to have been filled from it; although it is inconceivable in view of their exceeding smallness, at times only observable with a loupe, that they could have been filled from the molten matter.

"The fine black fusion lines, forming a confused network, run through the recognizable components in the midst of the mass; that is to say, the condrules and the rounded crystalline grains of olivine. The fusion lines mostly bend around the particles of pyrrhotite, though at times I noticed that the particles were traversed by the lines.

"The nickel-iron scattered through the silicate groundmass is silver-white in color. Most of the particles are smaller than in, for example, the Pultusk stone. Pyrrhotite appears rather

LONG LOST METEORIC STONES RECOVERED

STUART H. PERRY

THE recovery, after almost a century, of the two masses of the Girgenti meteorite, a white veined chondrite, makes a story of rather unusual interest to students and collectors in that line. Hitherto only fragments were known, aggregating 3,389 grams, but within the last year the writer has acquired the two stones vaguely mentioned by older writers—one of 8,750 grams and one of 2,151 grams.

Both specimens are in perfect preservation, showing well both the original fusion crust and the characteristic veined structure on broken surfaces. The smaller one is about half of its original size, the missing portion having furnished most of the fragments distributed sixty or seventy years ago to various collections.

The fall, which occurred in Sicily on February 10, 1853, near Girgenti (now Agrigento) was first mentioned by Greg in 1854 as "a large stone." A full petrographic description was published by Vom Rath in 1869, giving all the information then available on the history of the fall. The fragments then known, two of which he studied, aggregated less than 100 grams.

Wülfing in his exhaustive and meticulous listing (Die Meteoriten In Sammlungen, 1897) gave the total of all fragments of Girgenti as 3,389 grams. Though almost thirty years had elapsed since Vom Rath's paper, he knew nothing definite about the two main masses. He says: "Ursprüngliche Gewicht: mindestens 2 Steine. Greg sagt 'a large stone.' Buchner sagt 'der Stein wog 3-4 kg.' Nachweisbares Gewicht 3,389 gr."

The description of Girgenti by Vom Rath (Poggendorff's Annalen 138, pp. 541-545, 1869) is in part as follows:

"The stone that fell February 10, 1853, near Girgenti, Sicily, belongs among those meteorites that are little known, and only through samples in a few small collections. According to Professor Buchner the stone weighed 3 to 4 kg. Fragments of it are in the possession of Greg (9.2 gr), in Vienna (17.5 gr), London (7.02 gr), as well as in the Reichenbach collection, and finally those of Shepard and Nevill; while the prin-

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Brandon, Iowa

beds, generally regarded as Mississippian. This author has recently discussed these genera (1948, p. 103) and casts some doubt on their importance as decisive Devonian markers. Others may yet be found to occur in formations higher than Devonian as some Mississippian formations have as yet been incompletely explored for conodonts.

8. The Kinderhook succession in the Upper Mississippi valley seems to be as follows: 1. Maple Mill shale, 2. English River siltstone, 3. Louisiana limestone, 4. Hannibal shale and siltstone, 5. Chouteau limestone.

ACKNOWLEDGMENTS

The writer wishes to thank Dr. H. G. Hershey, Director of the Iowa Geological Survey, for permission to use information gained while a member of the organization. He also benefited much from discussions of the problem with Dr. Hershey and other members of the survey. However, the writer assumes full responsibility for the conclusions expressed in this paper.

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Louisiana beds are the same, it appears nearly conclusive that the latter is Mississippian.

Branson and Mehl have placed the Louisiana limestone in the Upper Devonian. Apparently this placement is based on evidence afforded chiefly by conodonts and by its stratigraphic relationships with the Grassy Creek shale. The writer believes that the usefulness of conodonts as stratigraphic markers has as yet not been completely determined. Likewise it is uncertain how much weight should be attached to them as evidence of geologic age, especially if conflicting with that given by other groups of fossils.

Branson and Mehl (1939) list five genera of conodonts as diagnostic of Devonian age. One, *Icriodus*, occurs in the Louisiana limestone with a macrofauna which Williams regards as Mississippian. In this opinion the writer is in full agreement since, as shown, above, the affinities of the Louisiana larger fossils are with those of the McCraney which are definitely Mississippian. The characteristic and unique microcrinoid, *Hybochilocrinus americanus* (Rowley), occurs in both terranes. Is not the evidence of age given by this crinoid as good as that of *Icriodus?*

Similarly L. A. Thomas lists the five conodont genera as present in the Maple Mill shale of Iowa and accordingly places the formation in the Devonian. The macrofauna, however, is plainly related to the Mississippian rather than to Devonian faunas. For instance the brachiopod *Chonopectus* occurs in the Maple Mill, in the English River and in the Louisiana (McCraney) of Iowa. Caster also lists it in the fauna of the Mississippian Corry sandstone of northeastern Pennsylvania. Moreover, besides faunal relationships the contact between the Maple Mill and the English River siltstone is a gradational one and does not appear to the writer to be intersystemic.

The Upper Devonian limit of the geologic ranges of these genera of conodonts does not seem to be established beyond reasonable doubt. The genera, *Ancyrodella, Polylophodonta* and *Palmatolepis* are said by Branson and Mehl (1933) to be present in the Bushberg of Missouri but are thought by them to be contaminants. *Ancyrognathus* is listed by Branson (1938, p. 334) in the Hannibal shale. *Palmatolepis* and *Icriodus* are said by C. L. Cooper to be present in the Upper New Albany

nibal formation as is shown by its fauna and stratigraphic position.

7. An early Mississippian age for the Louisiana limestone is indicated by its fauna and its stratigraphic situation above English River siltstone and Maple Mill shale, recognized by geologists generally as basal terranes of that system. Williams has recently considered at length the evidences for the assignment of the Louisiana to the Mississippian and his arguments need not be repeated here. A few comments on the fauna, inclusive of that of the McCraney, may be added. The Louisiana fauna as a whole has few of the aspects of any Devonian fauna known to the writer. None of the larger invertebrate species occurs in any known Devonian formation. Few, if any, of the distinctive genera of macrofossils of the Upper Devonian of the Mississippi valley are found in the Louisiana.

On the other hand Williams found that a number of Louisiana species do occur in recognized Mississippian formations. Five are present in the Prospect Hill siltstone at Burlington, four in the English River siltstone, four in the Glen Park beds, five in the Chouteau limestone, nine in the Waverly beds of Ohio and five in the Hannibal beds. It is true that many of the characteristic productids of the Mississippian are absent in the Louisiana. However, *Avonia*, represented by *Avonia pyxidata* (Hall) is present therein. It is not a true *Productella* as it lacks the high cardinal areas of that Devonian genus and has in addition radial plications on the front of the valve of many specimens. Others are quite smooth but this is readily explained by assuming that the developing genus had not yet attained its mature characteristics so early in the Mississippian. The presence of *Linoproductus ovatus* (Hall), a species with an extended range in the Mississippian and occurring in the northernmost exposures of the Louisiana limestone in Iowa, is highly indicative of the post-Devonian age of the terrane. The presence of *Chonopectus*, *Torynifer* and *Paraphorhynchus* is further support for this assignment.

The Maple Mill shale and the English River siltstone below the Louisiana limestone in Iowa include such genera of productids as *Linoproductus*, *Dictyoclostus* and *Krotovia*. In Franklin county, Iowa, the Louisiana overlies the Chapin bed which has an extensive Mississippian fauna as listed by Laudon (1931, p. 393, *Cyathaxonia* zone). If the McCraney and

than hitherto recognized, as its outcrops range from Franklin county, Iowa to Hardin county, Illinois.

3. The McCraney limestone is not a member of the Hannibal formation. Since the name Louisiana has precedence, the term McCraney may well be dropped.

If it is granted that the McCraney and Louisiana limestones are parts of the same formation it follows that the siltstones which lie above and below are different formations.

4. The English River siltstone is not a member of the Hannibal formation. This is favored by the difference in the faunas of the two terranes as appears in a study of Moore's lists (1928, p. 53). An inspection of the table of Hannibal species collected at Louisiana, Missouri, (disregarding the columns of collections at Rockport and Pleasant Hill which are Glen Park) shows that only five occur in the English River siltstone. This proportion is not large considering their similar lithology which is indicative of the same ecological environment. Also, fossils of these siltstones being molds exclusively are sometimes difficult to identify accurately. Finer differences are often obscured or lost. Faunally the English River is more definitely related to the Louisiana and Maple Mill in Iowa (Weller 1905, pp. 624-5).

5. The Hannibal formation is represented in Iowa and in the Kinderhook region of Illinois by the Prospect Hill siltstone. The macrofauna of the Prospect Hill is quite similar to that of the Hannibal as Moore states (1928, p. 21). This correlation is further strengthened by a study of Prospect Hill conodonts by Youngquist and Patterson who found them to be similar to those of the Hannibal. Furthermore the Prospect Hill has many species in common with the Northview sandstone of southwestern Missouri. That formation is said by Weller (1905, p. 633) to be equal to the Hannibal. Likewise the Prospect Hill may be traced below the surface into Hannibal beds (Harris, 1947).

6. The Maple Mill shale is apparently traceable in Illinois from Kinderhook south into the Saverton shale at Hamburg. They appear to be parts of the same body of shale. If so, Maple Mill has precedence by twenty-five years. The fauna of the Saverton in Missouri is related to the fauna of the Louisiana and the same is true of the fauna of the McCraney and the Maple Mill. The latter is not a member of the Han-

burg as the shale beneath simultaneously thins to a thickness of one foot.

The thick body of shale above the Glen Park beds at Hamburg, apparently Hannibal, becomes more silty so that at Rockport it is a thick body of siltstone lying on Glen Park. It may continue northward and overlap on English River. It would be difficult to distinguish them in the same section because of their lithologic similarity without Glen Park or Louisiana between. On the other hand the Hannibal may disappear to the northward of Rockport either through erosion or nondeposition. The abrupt disappearance of the Glen Park just north of Rockport lends credence to the possibility that the Hannibal does likewise. The writer was not able to trace the beds from Rockport to New Canton but does not believe that the Hannibal can be traced into the English River. The two terranes may occur, one above the other north of Rockport and would be hard to separate because of their lithologic similarity without the presence of formations which elsewhere occur between them. The possibility of confusion and variable interpretations of the beds north of Rockport is evident. On the other hand Harris (1947) states that there is subsurface information at hand that the Prospect Hill of Iowa thickens to the south and southeastward of Burlington until it merges with the Hannibal of Missouri. The siltstone above the McCraney north of Kinderhook, Illinois, would appear to be Hannibal.

The Burlington limestone can be traced continuously from Kinderhook to Hamburg, Illinois, as in the case of the Maple Mill. This is true also in Iowa where the Burlington and Maple Mill are continuous over large areas and enclose between them a number of discontinuous formations as the English River, Louisiana, Prospect Hill and others.

CONCLUSIONS

1. The lithologic and faunal similarity and apparently identical stratigraphic position of the McCraney and the Louisiana strata lead to the conclusion that they are portions of the same body of limestone. This substantiated by tracing the Louisiana in subsurface in northern Missouri into the McCraney in Iowa (Harris, 1947).

2. The extent of the Louisiana limestone is thus much greater

the McCraney. He has recognized the McCraney in Iowa as Louisiana. The isopach map of the Louisiana limestone by Williams (1943, p. 9) also favors this interpretation of the relationship between the Louisiana and the McCraney.

The Glen Park sandy dolomite and oolite can be traced almost continuously northward from Hamburg to Rockport. It lies on Louisiana at first, then on Maple Mill as the English River and Louisiana beds were eroded or were never deposited in the region between Rockport and north of Belleview. The Glen Park is seen at several places in Rockport but appears to end abruptly there, as it is not seen in section beyond to New Canton.

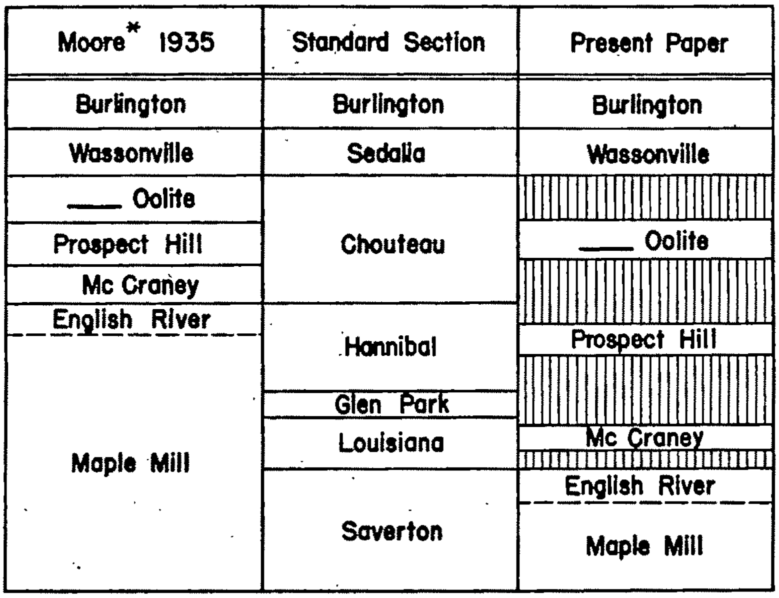
The stratigraphy of the lower Mississippian formations in the east wall of the Mississippi valley may be summarized from the sections given above and from outcrops not mentioned (fig. 1).

The Maple Mill shale of the Kinderhook section appears to be traceable almost continuously along the Mississippi bluffs into the Saverton shale at Hamburg. From a thickness of one foot at the latter place it increases in thickness to the northward, becomes less fissile, less black, more grayish and merges with the typical Maple Mill shale. As the base was not observed in most places, the thickness is unknown except at Hamburg. In no place did the writer observe this basal Kinderhook shale to unite with the Hannibal beds.

The English River siltstone rises gradually to the southward from Kinderhook and comes to underlie the Burlington limestone as the McCraney feathers out just north of New Canton. It may continue southward nearly as far as Rockport but at that place and beyond it has been removed so that Glen Park lies on Maple Mill. The English River siltstone is apparently absent for a considerable distance and next reappears a mile or so north of Belleview. In the south side of the valley of the first creek north of that place, it occurs immediately below Louisiana limestone, has its typical lithology, and is six feet thick with the base not exposed. This section is similar to some in the Kinderhook area of Illinois. The fact that both English River and Hannibal may be seen in the same section north of Belleview would seem to show that they are not correlatives. The siltstone disappears north of Ham-

A block of Glen Park oolite, not in place, indicates that it is present as well. The possibility exists that more than one siltstone is present here, but this can only be assured when the position of the Glen Park is known definitely.

The McCraney limestone north of Kinderhook has siltstone above and English River siltstone and Maple Mill shale below. The same stratigraphic positions of these beds are seen in the case of the Louisiana at Belleview. Since the lithology of the Louisiana and the McCraney is identical (Weller 1905, p. 624) and the fauna apparently the same, it seems probable that the two terranes are members of the same limestone body. In support of this is the observation of Weller and Sutton (1940, p. 785) that the two limestones have never been seen in the same section. S. E. Harris, Jr. (1947) has recently studied samples of wells from northeast Missouri and southern Iowa and has apparently traced the Louisiana limestone into



Figure—1 Correlation of Lower Mississippian of southeastern Iowa and northwestern Illinois discussed in this paper.

* Moore, R.C., 1935, Ninth Annual Field Conference, Kansas Geological Society, page 245.

of the county line. It will be noted that the Hannibal beds of the Hamburg section occur here in full force above the Louisiana limestone. Consequently the siltstone below, which the writer believes to be English River, appears to be a distinct terrane. Although the Glen Park beds are not seen in these sections, they are commonly present in a number of places as far north as Rockport.

Along the second creek north of Atlas (Jim Town Branch) about a half mile east of the highway is a good section showing the relationship of the Glen Park to the beds above.

4. Siltstone, Hannibal, blue, massively bedded, grading into bed below; higher beds upstream more shaly	5–6 ft.+
3. Shale, Hannibal, blue, elsewhere brown or intermottled with blue	4 ft.
2. Dolomite, Glen Park, buff, upper surface irregular	1–2 ft.
1. Limestone, Glen Park, oolitic; conglomeratic, pebbles of lithographic limestone, well rounded; dipping downstream; massively bedded above, weathering into thin plates below	5–6 ft.

Some distance downstream is a shale, apparently Maple Mill, as both English River and Louisiana formations have feathered out some miles to the southward.

At Rockport, Illinois, in an extensive ravine in the south part of town the same beds are again seen.

3. Shale and siltstone, Hannibal, blue	10 ft.+
2. Dolomite, Glen Park, blue when unweathered, buff, massively bedded, fossiliferous, sharp contact with shale below	6 ft.+ –
1. Shale, Maple Mill, considerable thickness, has two thin widely-separated layers of limestone	30 ft.+

In the north part of Rockport in a ravine a block north of the church is another section as follows, (thickness estimated):

6. Burlington limestone	6 ft.+
5. Siltstone, massive, wormlike markings 2–3 feet of shale at top, Hannibal?	20 ft.
4. Siltstone and shale, mostly covered	15 ft.
3. Shale, blue, mostly covered	10 ft.
2. Siltstone, massively bedded, resistant, fossiliferous, forming a declivity, English River?	15 ft.
1. Covered interval above road	80 ft.+

siltstone of the Kinderhook section. If true then the McCraney limestone must be younger and a separate designation would be warranted.

Since the Kinderhook beds concerned are exposed almost continuously in the east valley wall of the Mississippi and in tributary valleys from Kinderhook to Hamburg, an examination was made at a number of places which seemed to be critical in working out the stratigraphic relationships of the beds or where the rocks were best exposed and more accessible. Several observations were made of sections which appear to cast doubt on the correlation of the Hannibal and English River siltstones.

In the south bank of the first creek (Wild Cat Hollow) north of Belleview, Illinois, about a half mile east of the highway is an important section.

2. Louisiana limestone, lithographic with dolomite partings	30 ft.+
1. Siltstone, bluish, massively bedded, base not exposed, English River	6 ft.+

Louisiana limestone with typical fossils occurs at Hamburg about eleven miles south, and Belleview is across the river and southeast of the type locality of the Louisiana limestone at Louisiana, Missouri. Moore states (1928, p. 45) that the Louisiana limestone is present in Calhoun county, Illinois, and Williams (1943, p. 9) maps it as present in the county to the north as well. Consequently it appears certain that the upper terrane of the section is Louisiana limestone. The siltstone at the base is strikingly similar to the English River beds and the section duplicates some seen near Burlington, Iowa. If the siltstone is not the English River it is an hitherto undescribed terrane.

In the hill on the north side of the same valley and adjacent to the highway is another and more extended section.

3. Limestone, Louisiana	3–4 ft.
2. Siltstone, English River	4–5 ft.
1. Shale, Maple Mill, mostly covered	15 ft.

The section is continued about 100 yards farther north on the same hill.

5. Burlington limestone	30 ft.+
4. Shale, Hannibal	70 ft.+
3. Limestone, Louisana	15–20 ft.

The same section was also observed at a place a mile south

sections of these formations on the English River in Washington county, Iowa. The strata of this section dip below river level south of Burlington and next appear in the east wall of the Mississippi valley below Quincy, Illinois.

The Mississippian section near Kinderhook, Illinois is approximately:

4.	Burlington limestone	25+ ft.
3.	McCraney limestone	10
2.	English River siltstone	30
1.	Maple Mill shale	40+

There seems to be general agreement among geologists regarding the designation of the beds below the McCraney (Kansas Geol. Soc. Guidebook, 1941, p. 72). Weller (1905, p. 623) has found in the siltstone a fauna which he definitely states is English River. Several terranes between the Burlington and McCraney limestone are absent in the immediate vicinity of Kinderhook. However, a few miles to the northward a siltstone comes in between them and there appears little doubt that it is the southern extension of the Prospect Hill siltstone of Iowa. It also differs but little from the upper part of the Hannibal as seen in the western part of Hannibal, Missouri (Kansas Geol. Soc. Guidebook, 1941, p. 66).

At Hannibal, Missouri, about 16 miles west of Kinderhook, is a well-known section:

3.	Burlington limestone	100 ft.
2.	Hannibal shale and siltstone	70 ft.
1.	Louisiana limestone	30 ft.

In the region of Hannibal a considerable thickness of shale is seen (Williams, 1943, p. 24; Grohskopf, Hinchey and Greene, p. 15) below the Louisiana in several places.

The next important section is at Hamburg, Illinois, along the creek in the south part of town.

7.	Burlington limestone	
6.	Shale and sandy shale (Hannibal)	75 ft.
5.	Glen Park sandy dolomite and oolite	12
4.	Louisiana limestone	5
3.	Shale (Saverton)	1
2.	Cedar Valley limestone	5
1.	Silurian	20

Bed 3 is a dark shale and is thought by some geologists to be Saverton. Bed 6 apparently is Hannibal and is the terrane which Moore states can be traced into the English River

Limestone Co. the McCraney (Kansas Geol. Soc. Guidebook, 1941, p. 74) is reported to be about forty-seven feet thick. In Iowa it is about six to twelve feet thick in the region of Burlington and is at least ten feet thick in Franklin county.

The McCraney limestone extends northward along the bluffs of the Mississippi from a point a mile north of New Canton, Illinois, until it passes beneath river level about ten miles south of Quincy. It next appears at the surface near Burlington, Iowa, and extends northward along the west wall of the Mississippi valley to the southern part of Louisa county. Thence it occurs intermittently in the south wall of the Iowa river valley to Wellman, Iowa. A considerable gap in the outcrop, generally due to erosion, but partly to burial beneath glacial drift, occurs in the area between Iowa and Franklin counties. A small area in Geneva township and an outlier north of Maynes Creek in Franklin county are the northernmost surface occurrences of the McCraney limestone.

The McCraney seems to have been considered a distinct terrane by Moore chiefly because at Kinderhook, Illinois, it overlies a massive siltstone. This he correlated with the Hannibal formation in its more southerly exposures in the east wall of the Mississippi valley. If this correlation is correct, then the lithographic limestone, McCraney, could not be the same as the lithographic limestone, the Louisiana, lying below the Hannibal at Hannibal and Louisiana, Missouri. However, the writer does not regard as established beyond doubt the equivalency of the siltstone below the McCraney with the Hannibal above the Louisiana.

The stratigraphy of the beds involved may be profitably reviewed by first noting the strata in the Burlington region of Iowa. The well-known and much-studied Prospect Hill section of Iowa is as follows:

8.	Burlington limestone	25 ft.
7.	Wassonville limestone	5
6.	Oolite	8–4
5.	Prospect Hill siltstone	5
4.	McCraney limestone	10
3.	Oolite and shell limestone	1
2.	English River siltstone	18
1.	Maple Mill shale	25+

There is no doubt about the designation of the beds below the McCraney limestone as they can be traced into the type

dodgei Rowley, *Bembexia minima* Rowley, *Schuchertella louisianaensis* Williams, *Strophalosia beecheri* Rowley and *Mesoblastus* sp. are found elsewhere only in the Louisiana limestone. Perhaps more important is the occurrence in the McCraney of the characteristic microcrinoid, *Hybochilocrinus americanus* (Rowley). The identification was kindly verified by Dr. Marvin Weller. Hitherto it has only been found in a shale parting in the Louisiana limestone at Louisiana, Missouri. The only other species described from North America occurs in the Chouteau limestone of Missouri and differs sufficiently to be readily distinguished from the Louisiana form. Other echinodermal remains are common in the McCraney and resemble some of those seen in the Louisiana. Among them are examples of plates of *Platycrinus* and possibly of *Poteriocrinus*.

STRATIGRAPHIC EVIDENCE

The McCraney limestone was described and named by R. C. Moore (1928, p. 21) from outcrops near Kinderhook, Illinois, the type locality of the Kinderhook series. The name is derived from McCraney creek, a stream a mile or so north of Kinderhook. An extensive disused quarry a mile or so northwest of the road junction displays the Kinderhook beds in a section identical with that noted by Meek and Worthen in 1861 in their description of the Kinderhook. Moore correlated the limestone with a nearly identical formation at Burlington, Iowa.

The McCraney limestone is rather thinly and somewhat irregularly bedded. The major portion of the rock is usually lithographic in texture and light gray. Thin seams of clay or clayey material may occur between the layers. Portions of the rock adjacent to the bedding planes are often irregularly dolomitic and buff as contrasted with the remainder. The irregular distribution of the dolomitic buff portions gives a vertical face of the limestone a typical mottled appearance. In this feature and in its lithology the McCraney differs but little from the Louisiana limestone.

In thickness the McCraney formation varies from a feather edge near New Canton, Illinois, to about ten feet at the Pigeon Creek schoolhouse about eight miles north of Kinderhook and to twenty-five farther north. At the plant of the Marblehead

few exceptions they all occur in the Louisiana limestone. *Rhynchopora pustulosa* (White) probably equals *R. rowleyi* Williams and *Syringothyris halli* is near if not actually the same as *Syringothyris hannibalensis* (Swallow). Two notable exceptions are *Linoproductus ovatus* (Hall) and *Chonopectus fischeri* (N. and P.). The latter also occurs in the English River sandstone and in the Maple Mill shale. However, in these formations it has been reported only from Iowa and its absence from the limestone farther south is not remarkable. *Linoproductus ovatus* has been found only in the most northern occurrence of the McCraney limestone in Franklin county, Iowa, and is not present in the Burlington area. Its absence, then, in the southern McCraney outcrops is not surprising.

While the extensive macrofauna of the Louisiana limestone is mostly lacking in the McCraney, the species in common to the two terranes appears to be highly significant. The Louisiana limestone is notably barren in many localities, especially in the Hannibal region where Williams (1943, p. 23) noted his failure to obtain fossils. The major portion of the Louisiana beds is relatively unfossiliferous compared to the basal portion according to Moore (1928, p. 45). Therefore, the sparseness of the fauna of the McCraney, if the two formations are correlatives, may be explained in that it is the upper portion rather than the lower fossiliferous part of the Louisiana that is represented in the McCraney limestone of Iowa and Illinois. Again the McCraney limestone has scarcely been explored for fossils and may be expected to yield additional specimens on further search. On the other hand the macrofauna of the McCraney cannot be said to be as closely related to that of any other formation as it is to that of the Louisiana.

The evidence afforded by microfossils is even more emphatic in support of the correlation of the McCraney with the Louisiana. The occurrence and preservation of the microfossils is the same in the two terranes and appear to add weight to the suggestion that they are one limestone. The fauna in each is secured by collecting the shaly interlayer material from between otherwise barren beds of limestone. All species thus far secured from the McCraney and identified, namely, *Ambocoelia minuta* White, *Ambocoelia louisianaensis* Williams, *Selenella pediculus* Rowley, *Chonetes ornatus* Shumard, *Crania*

Platyceras sp.
Aviculopecten cf. *marbuti* Rowley

Samples also were collected of the interlayer material and were found to carry a fairly good microfauna. Among the forms are:

Ambocoelia minuta White
Ambocoelia louisianaensis Williams, common.
Selenella pediculus Rowley, common.
Chonetes ornatus Swallow, a brachial valve.
Allorhynchus cf. *currei* Rowley, a small example.
Crinoid columnals, common.
Crinoid plates of two types, including ***Platycrinus*** sp.
Blastoid remains similar to ***Mesoblastus*** sp.
Echinoid spines and plates.
Holothuroid plates.

Fauna of the Louisiana Limestone

The Louisiana limestone at Hannibal and Louisiana, Missouri, was studied at intervals over several years and a small fauna collected. Additional examples of a number of species were given to the writer by the late R. R. Rowley as well as nearly a pint of washed interlayer material abounding in microforms. The exposure of Louisiana near the Methodist Church at Hamburg, Illinois, yielded many fossils in a short period of time. Especially prolific is the microfauna secured there which contains a number of minute species described by Rowley and Williams. Many of these species are represented by dozens of well-preserved specimens. These collections have served as a source of comparative material in the study of the McCraney fauna.

Correlation of the McCraney Limestone

The fauna of the McCraney beds was compared with those of the various Kinderhook formations of the Upper Mississippi valley and with those of other terranes whose places in the Mississippian system have been questioned. Only one fauna was found to display any considerable similarity in specific and faunal composition. This is the fauna of the Louisiana limestone of Missouri and Illinois.

A critical review of the McCraney species shows that with

Syringothyris halli Winchell
Chonetes gregarius Weller

Van Tuyl adds
Allorisma sp.
Schizodus sp.
Chonetes sp.

The writer found *Chonetes ornatus* Shumard to be rather abundant in a quarry on the south side of North Hill, at Burlington, Iowa. Samples of interlayer material were collected at the North Hill and Starr Cave localities. Only the samples from the latter place proved to carry recognizable fossils. From them were recovered:

Selenella pediculus Rowley
Ambocoelia minuta White
Bembexia minimus Rowley
Crinoid columnals
Echinoid spines

The species, though few in number, are similar to those secured from the McCraney beds at Kinderhook, Illinois, and indicate that the McCraney beds at Burlington are correctly correlated with those in the latter area.

In Franklin county, Iowa, a limestone similar in appearance to the McCraney and having the same stratigraphic situation was recently studied by the writer. It has a fauna demonstrating that it is the northward extension of the McCraney limestone of the Burlington area. Macrofossils are common and well preserved and the following species were identified:

Dictyoclostus sp.
Linoproductus ovatus (Hall)
Paraphorhynchus striatocostatum (M. and W.)
Camarotoechia cf. *tuta* Miller
Rhynchopora rowleyi Weller
Syringothyris hannibalensis (Swallow)
Cranaena sp.
Schellwienella sp.
Chonopectus fischeri (N. and P.)
Torynifer sp. A mold of an exterior.
Grammysia hannibalensis Shumard
Bellerophon sp.

Microfauna

Locality 1, Kinderhook quarry

Selenella pediculus Rowley

Ambocoelia louisianaensis Williams

Crinoid columnals

Locality 2, first creek north of Pigeon Creek

Selenella pediculus Rowley

Ambocoelia louisianaensis Williams

Crania dodgei Rowley

Echinoid spines

Blastoid plates

Crinoid columnals

Locality 3, Seehorn Hollow

Selenella pediculus Rowley

Ambocoelia louisianaensis Williams

Crania dodgei Rowley

Chonetes ornatus Shumard

Schuchtertella louisianaensis Williams

One small example with large ribs is placed in the species.

Strophalosia beecheri Rowley

Ambocoelia minuta White

Hybochilocrinus americanus Rowley

A dozen well-preserved examples, some showing plates and oral structures.

Platycrinus radials

Poteriocrinus? basals

Common echinoderm fragments including crinoid columnals; echinoid spines, striated and similar to those in Louisiana limestone; sievelike holothuroid plates; blastoid ambulacra and plates similar to those illustrated by Williams as *Mesoblastus*.

Ostracodes

The McCraney limestone at Burlington, Iowa, has been investigated by Weller (1900) and Van Tuyl (1928). The first lists these macrofossils:

Chonopectus fischeri (N. and P.)

Paraphorhynchus striatocostatum (M. and W.)

Allorhynchus heteropsis (Win.)

Rhynchonella unica Winchell

Rhynchopora pustulosa (White)

concludes that the McCraney cannot be correlated with the Louisiana limestone on grounds which to the present writer are not established beyond dispute.

The foregoing summary is sufficient to indicate the present confusion in the minds of geologists regarding the age and correlation of various strata near or above the Devono-Mississippian boundary. Different lines of evidence apparently have led to divergent opinions of the stratigraphic position of the same formation. Especially is this true of the McCraney-Louisiana problem. The writer has recently secured evidences, both stratigraphic and faunal, which lead him to correlate the two beds. The faunal evidence is considered first.

Fauna of the McCraney Limestone

A few macrofossils were collected by H. G. Hershey and the writer in the quarry north of Kinderhook, Illinois, where the McCraney lies directly beneath the Burlington limestone and above the English River siltstone. A few others were found in the limestone in outcrops farther to the north. In general, search for macrofossils in the Illinois area proved disappointing. Therefore, samples of shaly and weathered material were collected from between layers of the McCraney in several localities. The first is from the larger quarry in the NE 1/4 sec. 15, T. 4 S., R. 7 W., the second from an outcrop on the first creek north of Pigeon Creek and the last two from two places in Seehorn Hollow in SE 1/4 NW 1/4, sec. 31, T. 3 S., R. 7 W. and .2 mi. down the creek.

The complete fauna secured in Illinois from the McCraney is as follows:

Macrofossils

Syringothyris hannibalensis (Swallow)

This may be *S. halli* which differs, as Weller remarks, only in size.

Chonetes ornatus Shumard

Dozens on slabs embedded in matrix.

Paraphorhynchus striatocostatum (M. & W.)

Crushed examples poorly preserved, but showing the typical external markings.

Rhynchopora pustulosa (White)

Avonia pyidata (Hall)

This species is reported by Weller.

geologists. Keyes (1895, p. 487) considered it as distinct from the Louisiana limestone which he states feathers out before reaching the Burlington area. Weller (1900, p. 79) in his studies of the fauna of the Kinderhook suggested that the McCraney (bed 4 of Burlington section) "may be considered with a fair degree of certainty, as the northern extension of the Louisiana limestone". But later (1901, p. 209) he casts doubt on this conclusion by stating that the bed in question "had little or nothing to suggest its correlation with the Louisiana limestone".

Moore studied this limestone at Kinderhook, Illinois, and at Burlington, Iowa, and came to the conclusion (1928, p. 21) that it and the Louisiana limestone were distinct terranes. Consequently he termed the lithographic limestone at Kinderhook, Illinois, the McKerney from a creek nearby and included it along with the English River siltstone and Maple Mill shale as members of the Hannibal formation. The name was later found to be more properly McCraney (Weller and Sutton, 1940, p. 784).

Laudon (1931, p. 369) in his studies of the Kinderhook beds of Iowa designated the McCraney limestone as the *Paraphorhynchus* zone of the North Hill member of the Hampton formation. He rejected the correlation of the limestone with the Louisiana stating that "the fauna, however, shows definitely that this is not true." He suggested (p. 371) its lithologic similarity to upper ledges of the Chouteau at Newark, Missouri. However the fauna of this bed as listed by Moore (1928, p. 63, zone 4) shows few or no typical McCraney fossils.

Williams (1943) gave in considerable detail the various opinions of and evidence for and against the correlation of the McCraney with the Louisiana and he concluded with Moore and Laudon that the McCraney is younger than Louisiana. He stated, however, that the correlations of Moore are based on incomplete evidences, many of them conflicting. He suggested that new facts will have to be discovered in order to correlate the Kinderhook beds at Kinderhook, Illinois, at Louisiana, Missouri and at Burlington, Iowa, with any degree of assurance.

L. A. Thomas (1949) has recently discussed the McCraney and Louisiana limestones incidental to his study of conodonts of several Mississippian formations of southeast Iowa. He

THE FAUNA AND CORRELATION OF THE McCRANEY LIMESTONE OF IOWA AND ILLINOIS

MERRILL A. STAINBROOK

ABSTRACT. Recent collections of fossils from the McCraney limestone in Iowa and Illinois and study of several sections of the Kinderhook strata along the Mississippi River have yielded new facts concerning the age and relationship of the terrane. Evidences cited favor the correlation of the McCraney with the Louisiana formation. Faunally, lithologically and stratigraphically the two terranes seem to be members of the same body of limestone.

INTRODUCTION

IN the basal Kinderhook beds of Iowa and Illinois occurs the McCraney limestone, generally lithographic, and with characteristic physical appearance. Its stratigraphic position with reference to other Kinderhook beds and its correlation have been subject to various interpretations in the past. The present paper, the result of investigations made for the Iowa Geological Survey in 1946-47 and the writer's own studies, presents new evidence which may aid in settling the problem satisfactorily.

In northeast Missouri in the vicinity of the Mississippi River and in west-central Illinois a similar limestone has long been known and its extensive fauna studied by several investigators. It was called the Louisiana limestone by Keyes (1892, p. 289). Rowley described the formation as it occurs in Pike County, Missouri, and gave diagnoses and illustrations of many of its fossils. Weller (1914) described and illustrated many of its brachiopods. Williams has lately given a monographic survey of the formation and of its fauna. He considered the formation to be lower Mississippian in age and gave a complete summary of the evidence therefor.

The Louisiana limestone has generally been considered to be a member of the Kinderhook series of the Mississippian system. Recently Branson and Branson and Mehl, chiefly on the basis of the occurrence of the conodont genus, *Icriodus*, have suggested that the limestone is upper Devonian in age.

The McCraney limestone in the Kinderhook sections at Burlington and Kinderhook has been studied by a number of

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Holotype: U.S.N.M. 560475; paratypes: U.S.N.M. 560477; figured paratype: U.S.N.M. 560476.

Vorticifex globosus Yen, n. sp.
Pl. 1, figs. 14, 14a.

Shell globose in outline, with low but elevated spire and inflated body whorl. Whorls roundly convex, rapidly increasing in size, rounded at the periphery and obscurely angulated at the base. The sculpture consists of fine growth lines and strong riblets. Aperture descending, pyriform in outline; peristome thin and continuous, umbilicus moderately open.

Altitude of shell	13.5	13.0
Width of shell	15.0	15.0
Height of aperture	9.0	9.5
Width of aperture	8.0	8.0
Diameter of umbilicus	4.0	4.0
Number of whorls	4	4

This species differs from *V. tryoni* by its smaller size, more globose outline, more roundly convex whorls, and decidedly descending aperture. It is characterized by its globose outline, small size, and narrowly opened umbilicus. It has some features of both *V. tryoni* and *V. t. concavus*.

The elevation of the spire seems to be variable, though it never becomes very depressed. The aperture of the younger forms is nearly circular in outline.

Holotype: U.S.N.M. 560478; paratypes: U.S.N.M. 560480; figured paratype: U.S.N.M. 560479.

Vorticifex binneyi (Meek)
Pl. 1, fig. 17.
Acad. Nat. Sci. Philadelphia Proc., 22, p. 59, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 187, pl. 17, figs. 11, 11a, 1877.

This species is characterized by its large size (the largest example in the present collection is 20.0 mm. in altitude of shell, 27.0 in width; 14.2 in height of aperture and 14.0 in its width; and has a little over 4 whorls), carination along the periphery and also around the umbilicus, and very rapidly increasing whorls. The younger forms have an excavated and widely open umbilicus, more or less flatly depressed spire, and a descending aperture.

Figured specimen: U.S.N.M. 560481; additional specimens: U.S.N.M. 560482.

This form differs from the species by having a sunken apical whorl and subsequent whorls more strongly convex, more rapidly increasing in size. It bears more or less strongly developed riblets in addition to the distinct lines of growth.

Figured specimens: U.S.N.M. 560470 and 560471; additional specimens: U.S.N.M. 560472.

Vorticifex tryoni planus Yen, n. subsp.

Pl. 1, fig. 16.

This form is differentiated from *tryoni* s. s. and *t. concavus* by its much smaller size, more planorboid outline, much less rapid increase in size of whorls, and its wider umbilicus.

Altitude of shell	6.2	5.5
Width of shell	12.5	11.2
Height of aperture	5.5	6.0
Width of aperture	4.8	5.0
Diameter of umbilicus	3.0	3.0
Number of whorls	4¼	4

Holotype: U.S.N.M. 560473; paratypes: U.S.N.M. 560474.

Vorticifex menetoides Yen, n. sp.

Pl. 1, figs. 15, 15a.

Shell of planorboid outline, comparatively small in size for the genus. The whorls are rather flatly convex and rapidly increase in size. The body whorl is laterally inflated and slightly descending, which features produce a gently convex appearance of the shell in apical view. The periphery is obscurely angulated and roundly convex at the base. The sculpture consists of lines of growth and distinct but weak riblets. Aperture transversally ovate, peristome thin and continuous. Umbilicus moderately wide.

Altitude of shell	3.7	4.0
Width of shell	9.1	10.0
Height of aperture	3.1	3.6
Width of aperture	4.2	4.2
Diameter of umbilicus	3.0	3.0
Number of whorls	4½	4

This species differs from *V. t. planus* by its much smaller size, more flatly planorboid outline, and wider umbilicus. It is represented by several score of examples in the present collection, and they are found in association with *V. tryoni* and related forms.

This apparently extinct genus is represented in the present fauna by the six species and subspecies described below. All these forms are apparently more or less related, but they are sufficiently differentiated from each other by distinct features of both adult and young stages. The speciation of these forms is illustrated by figure 1, in which the solid line indicates the relationships of all the forms involved, on the basis of similarity in their morphological features, while the broken line indicates uncertainty of connections.

Vorticifex tryoni is represented in the present collection by more individuals than any one of the remaining five forms. *V. t. concavus* and *V. menetoides* rank next in abundance, and the other three all have several to a score of examples in the collection. The greater number of individuals of *V. tryoni* imply that it is possibly an "elementary species" of the genus. Others seem to be related to it, and some may possibly be evolved through hybridization.

Vorticifex tryoni (Meek)

Pl. 1, figs. 12, 12a.

Acad. Nat. Sci. Philadelphia Proc., 22, p. 59, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 188, pl. 17, fig. 10, 10a-b, 1877.

This species is one of the dominant forms in the Truckee beds. It is represented by a large number of individuals. The peripherial angulation ranges from distinct to obscure, and the typical form is rather rounded at the periphery. The younger individuals have a descending aperture large in proportion to the size of the shell and are readily separable from the young individuals of the related forms. Meek's variety *ventricosa* (1870, p. 60) does not bear sufficiently distinct features to warrant a separation. The body whorl of this species is more or less ventricose, and its appearance is somewhat determined by the outline along the periphery of the body whorl, whether angulated or smoothly rounded.

Figured specimens: U.S.N.M. 560464 and 560465; additional specimens: U.S.N.M. 560466 to 560469.

Vorticifex tryoni concavus (Meek)

Pl. 1, figs. 13, 13a.

Acad. Nat. Sci. Philadelphia Proc., 22, p. 60, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 189, pl. 17, fig. 10c, 1877.

1 to 1.5 mm. in diameter of shell, but it differs by having less rapidly increasing whorls and being distinctly carinated along the periphery. The differentiation of the two forms in the same fossil bed is readily effected. Its occurrence is less common in the deposit than that of the preceding species.

Figured specimen: U.S.N.M. 560462; additional specimens: U.S.N.M. 560463.

VORTICIFEX MEEK

The genus *Vorticifex* Meek is represented by species from the late Tertiary beds in Nevada and Idaho, so far as the previous records are known. A few forms that have been referred to this genus may belong to *Carinifex* or other genera.

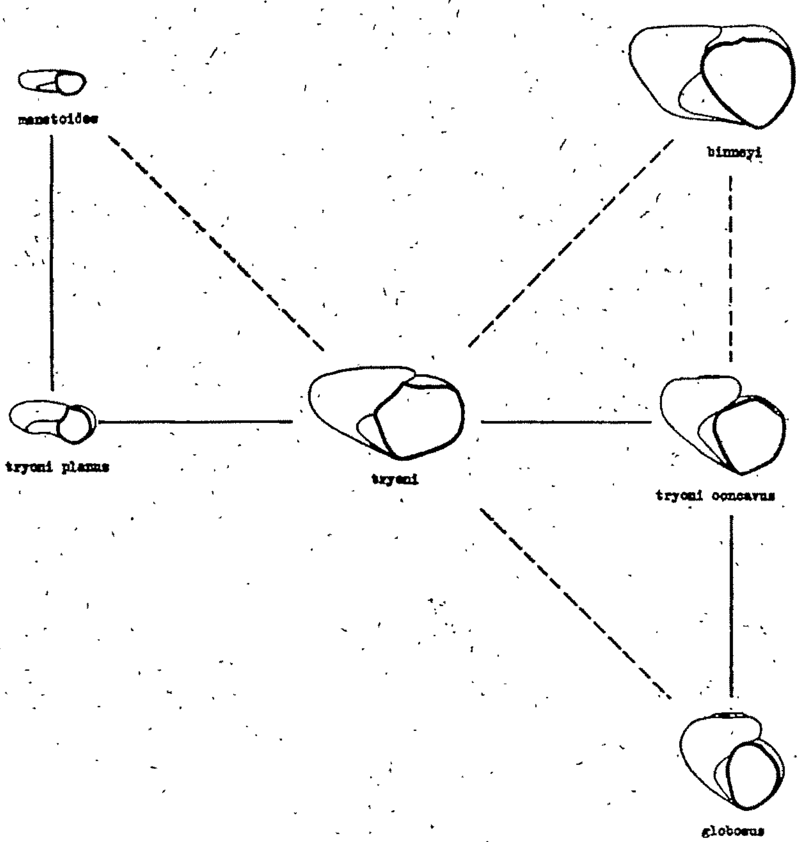


Fig. 1. Speciation of *Vorticifex* Meek — the illustrations are natural size, solid line shows possible derivations of the "elementary species," uncertain connections of species are indicated by broken line.

Figured specimens: U.S.N.M. 560451, 560452 and 560453; additional specimens: U.S.N.M. 560454.

Goniobasis cf. G. arnoldiana Pilsbry

Pl. 1, fig. 9.

Nautilus, 48, p. 15, 1934; Acad. Nat. Sci. Philadelphia Proc., 86, p. 547, pl. 18, figs. 6, 6a, 7, 1935.

Five specimens in the collection are comparable to *Goniobasis arnoldiana*, but they differ from the Tulare species from California by their much smaller size, more slender outline, and more convex whorls. They probably represent a distinct species, but a full description will have to be based on specimens in more perfect state of preservation.

Figured specimen: U.S.N.M. 560455; additional specimens: U.S.N.M. 560456.

Family Lancidae

Lanx undulatus (Meek)

Pl. 1, figs. 10, 10a, 10b.

Acad. Nat. Sci. Philadelphia Proc., 22, p. 57, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 186, pl. 17, fig. 12, 1877. (*Ancylus*)

This is one of the common species of the Truckee formation and is represented by many specimens in the present collection. The available examples show a range of variation in altitude of shell. This species is also reported from several localities in the Idaho formation, of Pliocene age, in the southern part of Idaho.

Figured specimens: U.S.N.M. 560458 and 560459; additional specimens: U.S.N.M. 560460.

Family Planorbidae

Gyraulus sp. undet.

About a dozen rather imperfect specimens represent this small form of *Gyraulus* in the collection. Most of them consist of 2 to 3 gently convex and rapidly increasing whorls. No characteristic features are noticeable, and their specific identity is at present undeterminable.

U.S.N.M. 560461.

Menetus sp. undet.

Pl. 1, figs. 11, 11a.

This form is of nearly the same size as the preceding one,

Lacunorbis Yen, n. gen.

Shell trochoid in outline, perspectively umbilicated, with a few tubular and closely coiled whorls, more or less carinated along the periphery. Aperture angulate-ovate in outline, descending, and more or less attached to the penult whorl.

Genotype: *Lacunorbis nevadensis* Yen, n. sp.

The new genus is reminiscent of *Brannerillus* Hannibal, from Miocene and Pliocene deposits in western North America, and *Cochliopa* Stimpson, in the Recent fauna distributed over California, Texas, and Central America. The genus is characterized by its trochoid outline, perspective umbilicus, and its tubular whorls.

Lacunorbis nevadensis Yen, n. sp.

Pl. 1, figs. 7, 7a, 7b.

Shell of small size, about 3 mm. in diameter, with a slightly raised apical whorl and conically elevated spire. Whorls moderately rapidly increasing in size, tubular, and closely coiled, with their surface slightly convex, strongly carinated at the periphery, and bearing fine lines of growth. Aperture descending, barely attached to the preceding whorl, angularly ovate in outline. The umbilicus is about two-thirds of the diameter of the shell.

Altitude of shell	2.5	2.0	1.7
Width of shell	3.0	2.8	2.7
Diameter of aperture	0.8	0.6	0.5
Diameter of umbilicus	1.5	1.4	1.2
Number of whorls	4	3¾	3¼

The species is characterized by its small size, with closely coiled whorls and strongly carinated periphery.

Holotype: U.S.N.M. 560443; paratypes: U.S.N.M. 560446; figured paratypes: U.S.N.M. 560444 and 560445.

Family Pleuroceratidae

Goniobasis sculptilis (Meek)

Pl. 1, figs. 8, 8a, 8b.

Acad. Nat. Sci. Philadelphia Proc., 22, p. 58, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 195, pl. 17, fig. 8, 1877.

This is a quite common species in the Truckee beds. The present collection contains specimens representing several stages in development. The width of shell seems to be quite variable, a few examples being more slender in outline than the typical forms.

Measurements (given in mm. for this and all the following species): Shell 2.4 in altitude, 2.0 in width; aperture 1.0 in height, 0.7 in width; 3¾ whorls.

This species resembles *Amnicola longinqua* Gould but differs by its more globose outline, smaller size, and shorter spire. *Amnicola longinqua* has been frequently reported from the Recent fauna as well as from Pleistocene beds.

Holotype: U.S.N.M. 560438; paratypes: U.S.N.M. 560439; figured paratypes: U.S.N.M. 560447 and 560448.

Fluminicola yatesiana inflata Yen, n. subsp.

Pl. 1, figs. 5, 5a.

This subspecies differs from the typical form, which was originally described from Pliocene beds in California, by its much smaller size, with similar number of whorls, more rapidly inflated body whorl, and more acute angle of spire. It differs from *F. y. utahensis* Yen, which was described from Pliocene beds in northern Utah (1947, p. 278, pl. 48, fig. 6), by its more strongly convex whorls and more inflated body whorl. The holotype is 3.5 mm. in altitude, 2.8 mm. in width, and has 4½ whorls.

Holotype: U.S.N.M. 560440; paratypes: U.S.N.M. 560441; figured paratype: U.S.N.M. 560442.

Hydrobia truckeensis, Yen, n. sp.

Pl. 1, fig. 6.

Shell minute in size, subovate in outline; spire greater than the body whorl. Whorls strongly convex, moderately rapidly increasing in size and bearing fine lines of growth. Aperture descending, cardiform in outline, and barely attached to the penult whorl. Peristome thin and continuous. Umbilicus narrowly perforate.

Altitude of shell	2.1	2.0
Width of shell	1.3	1.3
Diameter of aperture	0.6	0.6
Number of whorls	4	3½

The size and outline of this species approach closely those of *Hydrobia andersoni* (Arnold), a Tulare species from California. However it differs by having fewer whorls and shorter spire.

Holotype: U.S.N.M. 560449; paratypes: U.S.N.M. 560450.

Figured specimen: U.S.N.M. 560432; additional specimens: U.S.N.M. 560433.

Family Valvatidae

Valvata cf. V. incerta Yen

Pl. 1, fig. 2.

Jour. Paleontology, 21(3), p. 272, pl. 43, figs. 4a–c, 1947.

This form is more planorboid in outline than *V. incerta*, which was described from a Pleistocene deposit of Utah, and it is obscurely angulated along the periphery of the body whorl. The illustrated specimen is well preserved, whereas a few other examples retain only their early whorls. It is probably a distinct species of *Valvata*, but the material available at present does not permit a full description of a species.

Figured specimen: U.S.N.M. 560434; additional specimens: U.S.N.M. 560435.

Valvata truckeensis, Yen, n. sp.

Pl. 1, fig. 3.

This species resembles the one recorded as *Valvata* sp. undet. from a Miocene deposit exposed near Montpelier, Idaho (Yen, 1946, p. 488, pl. 76, fig. 3). It is characterized by its small size (1.9 mm. in altitude, 2.0 mm. in width, with a little over 3 gently convex whorls), globose outline of shell, elevated spire, descending body whorl, and circular aperture; its umbilicus is about one-third the diameter of the shell.

It is smaller in size and has less convex whorls and wider umbilicus than the Miocene form recorded from Montpelier, Idaho.

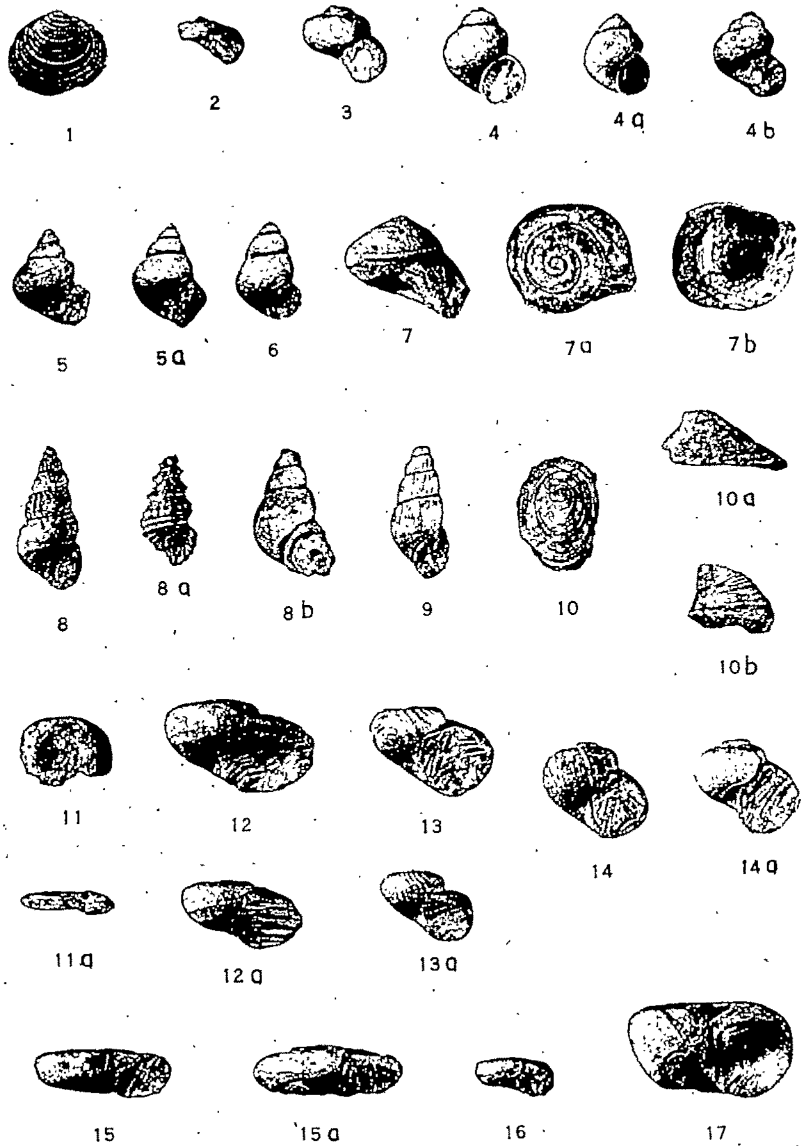
Holotype: U.S.N.M. 560436; paratypes: U.S.N.M. 560437.

Family Amnicolidae

Amnicola truckeensis, Yen, n. sp.

Pl. 1, figs. 4, 4a, 4b.

Shell small in size, subglobose in outline, having a short but elevated spire and an inflated body whorl. Whorls roundly convex, moderately rapidly increasing in size; surface bearing fine lines of growth. Aperture cardiform in outline, descending, barely attaching to the preceding whorl. Peristome continuous and thin; inner lip margin slightly expanded. Umbilicus narrow but open.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SYSTEMATIC ACCOUNT OF THE MOLLUSCAN SPECIES

Family Sphaeriidae

Sphaerium rugosum Meek

Pl. 1, fig. 1.

Acad. Nat. Sci. Philadelphia Proc., 22, p. 56, 1870; U. S. Geol. Expl. 40th Par. Rept. 4(1), p. 182, pl. 16, figs. 2, 2a, 2b, 1877.

A number of closed shells and single valves that represent different stages in development seem to agree well with this species. The better-preserved specimens show distinctly the concentric growth lines noted by Meek. The illustrated specimen represents a young stage with well-preserved sculpture.

EXPLANATION OF PLATE

Fig. 1. Sphaerium rugosum Meek. X2.

Fig. 2. Valvata cf. V. incerta Yen. X6.

Fig. 3. Valvata truckeensis Yen, n. sp. X6. Holotype.

Fig. 4. Amnicola truckeensis Yen, n. sp. X6.
  4. Holotype.
  4a, 4b. Paratypes.

Fig. 5. Fluminicola yatesiana inflata Yen, n. subsp. X4.
  5. Holotype.
  5a. Paratype.

Fig. 6. Hydrobia truckeensis Yen, n. sp. X6. Holotype.

Fig. 7. Lacunorbis nevadensis Yen, n. gen. and sp. X6. Holotype.
  7. apertural view.
  7a. apical view.
  7b. basal view.

Fig. 8. Goniobasis sculptilis (Meek).
  8. an adult form. X1.
  8a. a young form with sculpture preserved. X2.
  8b. a young form with sculpture not preserved. X4.

Fig. 9. Goniobasis cf. G. arnoldiana Pilsbry. X2.

Fig. 10. Lanx undulatus (Meek).
  10 and 10a. adult specimens. X1.
  10b. a young form having higher altitude of shell. X2.

Fig. 11, 11a. Menetus sp. undet. X6.

Fig. 12, 12a. Vorticifex tryoni (Meek). X1.

Fig. 13, 13a. Vorticifex tryoni concavus (Meek). X1

Fig. 14. Vorticifex globosus Yen, n. sp. X1.
  14. Holotype.
  14a. Paratype.

Fig. 15. Vorticifex menetoides Yen, n. sp. X2.
  15. Holotype.
  15a. Paratype.

Fig. 16. Vorticifex tryoni planus Yen, n. subsp. X1. Holotype.

Fig. 17. Vorticifex binneyi (Meek). X1.

pleuroceratid shells were drifted ashore in quantity by currents, and the shore snails accidentally crept into the dead shells.

The new genus *Lacunorbis* will give no particular indication of its habitat until its relationships with Recent genera are better established. Since it is found in the present assemblage, it is probably a form of lacustrine habitat.

AGE OF THE DEPOSIT

The Truckee group was assigned by King (1878, p. 412) to a Miocene age. At the time (1870) Meek described the species of mollusks in King's collection, he considered it to be "apparently of Miocene or later age." This age assignment has been much questioned and discussed by authors during the last three-quarters of a century, but the deposit has been placed within the range of Meek's "Miocene or later."

On the evidence of the molluscan species, the assignment to a Miocene age seems to be favored only by presence of abundant individuals of *Vorticifex tryoni* and its varieties. These forms have been recorded from Miocene beds in southeastern Idaho (Yen 1946). However, the species has also been recorded from a number of Pliocene localities in Idaho, Utah, and Nevada, and its value as an age indication is thus reduced. On the other hand, *Vorticifex tryoni* and its varieties are here recorded together with *V. binneyi* and *Lanx undulatus*. A similar assemblage of species has been reported from the Idaho formation, of Pliocene age. Moreover, species of *Valvata, Amnicola, Fluminicola, Hydrobia,* and *Goniobasis* found in the present collection show close resemblance to the congeneric forms that have been described from Pliocene beds in Utah and the Tulare beds in California. Such morphological resemblance may well imply closeness in age.

It is clear then on the evidence of a few identifiable species of gastropods that the age of the type section of the Truckee formation is more likely to be Pliocene than Miocene. This conclusion seems to have been anticipated, however, in a quite noncommittal statement by Buwalda (1914), who on the evidence of a proboscidean tooth infers that the typical Truckee is "middle or upper Miocene or later." His statement seems to have been endorsed later on by Simpson (1933), who also considers that the Truckee beds are "at least as young as the middle Miocene, probably considerably younger."

The fossils are imbedded in a soft calcareous rock of coarse texture. In the course of preparation of the specimens, two kinds of matrix have been noted: one of creamy color containing dominantly species of *Vorticifex*, *Lacunorbis*, and *Lanx*; and a second pale gray in color and rich in species of *Goniobasis*. They seem to represent two different horizons or two distinct facies. Further investigation in the area would be required to reveal the significance of the apparent difference in the molluscan assemblages.

An assemblage rich in species and prolific in individuals generally implies a large size for the extinct body of water in which the fauna lived. The molluscan elements also seem to show that it was probably bordered in part by muddy shores and in part by stony shores. Considerable range of variation in size, sculpture, and altitude of shells in several of the species of gastropods here contained may possibly indicate different velocities of current and fluctuations of hydrogen-ion concentration of the water.

The rissoid and planorbid snails abundant in this fauna generally require a habitat area with a rich growth of an aquatic flora, either masses of filamentary algae or leafy plants, or both. Species of *Amnicola* and *Fluminicola* generally live on submerged vegetation that may be exposed to some current and on stems and leaves of reeds near the shore. Species of *Vorticifex*, *Menetus*, and *Gyraulus* primarily live on submerged plants of muddy and stony bottoms, especially among the vegetation near the shore. These planorbid snails are not rheophilous, but they can exist in moderate current. The freshwater limpets, such as species of *Lanx*, prefer a rocky bottom with vegetation in still water, though they may also exist in places where there is a slight current. Since the limpets live on diatoms and other algae as their food, the presence of such snails over the area may well imply also the presence of such lower plants.

The pleuroceratid forms, such as those of *Goniobasis*, may be variable in sculpture according to the hydrogen-ion concentration of the water. In general they are considered to be fluviatile forms, but they have been found to exist equally well in large lakes. Numerous specimens of *Goniobasis sculptilis* in the present collection are found to contain shells of young rissoid and planorbid species. It seems certain that these

Carinifex (Vorticifex) binneyi Meek, 1870
Carinifex (Vorticifex) tryoni Meek, 1870
Carinifex (Vorticifex) tryoni var. *concava* Meek, 1870
Melania? sculptilis Meek, 1870
Melania? subsculptilis Meek, 1870

C. A. White (1883) recorded a group of freshwater molluscan species from the "Truckee Group," exposed "about 50 miles below Salmon Forks, Snake River," Idaho. In addition to the seven species noted in Meek's list above, White reported the following additional species of gastropods:

Melania taylori Gabb
Lithasia antiqua Gabb
Latia dalli White

These additional species have been later reported from the Idaho formation by Dall (1924) and Yen (1944).

COMPOSITION OF THE FAUNA AND ITS HABITAT

The molluscan fauna from the type section of the Truckee formation, so far identified in the present collection, consists of the following species:

Sphaerium rugosum Meek
Valvata cf. *V. incerta* Yen
Valvata truckeensis, n. sp.
Amnicola truckeensis, n. sp.
Fluminicola yatesiana inflata, n. subsp.
Hydrobia truckeensis, n. sp.
Lacunorbis nevadensis, n. gen. and sp.
Goniobasis sculptilis (Meek)
Goniobasis cf. *G. arnoldiana* Pilsbry
Lanx undulatus (Meek)
Gyraulus sp. undet.
Menetus sp. undet.
Vorticifex tryoni (Meek)
Vorticifex tryoni concavus (Meek)
Vorticifex tryoni planus, n. subsp.
Vorticifex menetoides, n. sp.
Vorticifex globosus, n. sp.
Vorticifex binneyi (Meek)

A MOLLUSCAN FAUNA FROM THE TYPE SECTION OF THE TRUCKEE FORMATION

TENG-CHIEN YEN

ABSTRACT. Nineteen species and subspecies of freshwater mollusks are recorded from a saccharoidal limestone bed in Nevada. Previous records of the same formation exposed in this and its neighboring localities are reviewed. One genus and eight species and subspecies are herein described as new. This assemblage of molluscan species seems to indicate a Pliocene age of its enclosing rocks; it also indicates possibly a large size for the extinct body of water, bordered in part by muddy and in part by rocky shores; and the former existence of a rich growth of aquatic vegetation in the water.

A COLLECTION of invertebrate fossils, made by Dr. Daniel I. Axelrod, of the University of California at Los Angeles, from the type section of the Truckee formation in western Nevada, through the kindness of the collector, was submitted to me for examination and is the basis of the present paper. The fossil site, according to the information furnished by Doctor Axelrod, is shown on the U. S. Geological Survey's Carson Sink topographic sheet, "two miles north of the triangle marking the position of the Desert Queen Mine, which lies in the northeastern corner of the Hot Springs Mountains." No specific data concerning the stratigraphic position of the fossil bed were supplied.

The locality is evidently that of the fossiliferous deposit described by King (1878, p. 416) as his no. 3 bed of the Truckee group, which bed consists of saccharoidal limestone, 60 feet in thickness and bearing a rich content of freshwater mollusks. Meek (1870) described King's collection, citing the locality as "Hot Springs Mountains, at Fossil Hill, Idaho Territory." Meek later (1877) recorded this same group of species as from "Fossil Hill, Kaw-soh Mountains, Nevada." After a full consideration of the existing data, Reeside has pointed out (in Henderson, 1935, p. 49) that Hot Springs Mountains and Kaw-soh Mountains are identical, and the present collection of mollusks is undoubtedly from the same area. Meek recorded the following species:

Sphaerium rugosum Meek, 1870
Sphaerium idahoense Meek, 1870
Ancylus undulatus Meek, 1870

however, are still accompanied by local earthquakes and by emissions of considerable masses of pyroclastic materials and bombs projected to great distances. It is also noteworthy that the fumaroles when observed by the writer in 1947 seemed to be as active as when described by Reiss 78 years ago.

All these factors of the past and present activity of Puracé tend to indicate that the volcano has not greatly reduced its explosiveness in the last century and, although it seems to have passed the stages of the magmatic eruptions of its earlier history, it can still be considered as one of the very active volcanoes of the Andes.

The fact that the other volcanic cones of the Puracé Range to the south, as well as the volcano Sotará to the west appear inactive in recent times, would suggest that the tectonic adjustment of this zone of crustal weakness of the Andes is nearing its completion. The activity of Puracé is, therefore, the only remnant of a formerly far greater plutonic activity in the Cordillera Central of Colombia.

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Bogotá, Colombia

these bombs formed cavities in the tuff-bed of the cone; some of them 4 to 5 meters wide and 2 meters deep. True lava bombs, although present, were not as frequent as the angular volcanic blocks (plate 1, fig. 2). Some of the bomb cavities appeared to have been made by blocks which were projected to the surface the morning of the ascent or a day or two previous, since the cinder beds were freshly disturbed.

The deeply cut gorge immediately below the second fumarole is the source of Rio Vinagre. Within a mile it opens into a deep cut in the western flank of the mountain, where are displayed effects of large, recent mud-flows.

When visited by the writer the cone was totally free of ice and snow, and the deep rib-like grooves described by Reiss (1921) at its top were absent. There was likewise no visible trace of the small lake on the floor of the crater as described by that author in 1868.

CHARACTER OF ERUPTIONS

The periodicity of the eruptions of Puracé has not as yet been determined. Most of the investigators who have studied it from a close distance during the past century found it in some form of activity.

On many clear mornings the workmen of a sulphur mine near Puracé, at an altitude of 3,600 meters, have reported seeing a tall column of smoke rising above the volcano. The old inhabitants of the region have observed that the Puracé eruptions are particularly frequent during the months of May and June; these are the rainiest months in this part of the country. It seems possible, therefore, that the explosive eruptions are particularly strong during these months because of infiltrations of meteoric waters into the crater.

The cause of the sporadic activity of the volcano in recent times would have to be looked for in the apparently continuous expansion of juvenile gases fed to the crater from some depth. These, however, do not seem to have been accompanied by lava-flows. Judging by the early description of the volcano the character of the explosions does not seem to have changed much in the last century. The fact that great mud-flows have accompanied eruptions in the past and do not occur today is due to the deglaciation which has been followed by the complete melting of the formerly existing snow cap. The eruptions,

on the eastern flank of Puracé but could not be properly investigated.

The crater of Puracé, when observed in 1947 had a diameter of about 500 meters. It was totally made up of ashes, tuffs and other pyroclastic materials. The outer flanks have an inclination of about 30°. The inner walls, however, appeared

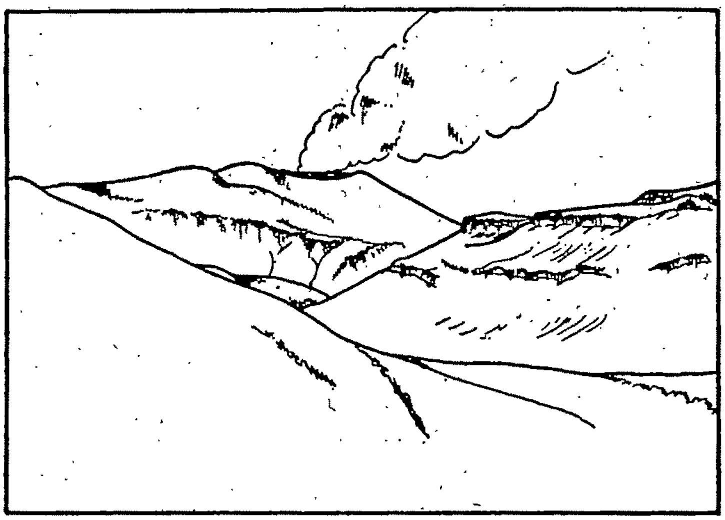

Fig. 2. View of Puracé in eruption in 1947 (from photograph by author).

much steeper and descended some 50 meters from the outer rim of the crater. At that level began the steep walls of the inner crater, issuing a column of steam, smoke and ashes.

Two fumaroles were observed some 150 meters from the rim of the crater on the outer western flank of Puracé. The smaller one, situated a little to the north and somewhat higher, was emitting steam in short periodic intervals simulating a steam engine. The second fumarole, a little lower and more to the south than the first one, showed a deep, wide cavity in the flank of the volcano and appeared surrounded with lava-flows, as well as layers of sulphur. It was emitting steam under less pressure than the first one.

The thick cover of pyroclastic materials forming the cone of Puracé consists predominantly of lapilli, with many large angular blocks of andesite which were torn out of the walls of the conduit of the volcano (plate 1, fig. 1). Some of the observed blocks were about 6 meters wide and 2 meters high. Upon falling,

PLATE 1

Fig. 1. Pyroclastic materials on the flanks of Puracé. In the center, cavity made by volcanic bomb (photograph by author).

Fig. 2. Typical volcanic bomb of Puracé (photograph by author).

mountain by 1934. At the time of the writer's visit to the crater there were found no traces of perpetual snow or ice; and a snow which fell on top of the mountain at this time melted instantly. The temperature at about 3:00 P.M. was 9° centigrade.

The lack of ice and snow on Puracé in recent times is largely due to the general process of deglaciation that is affecting the Andes (Oppenheim, 1948). The possible lowering of the crater due to successive explosions is also a consideration which, in the case of Puracé, should not be overlooked. On the other hand, there is evidence that recent eruptions have contributed to the growth of the volcanic cone.

GEOLOGY OF PURACE

Metamorphic crystalline slates are observable in the river valleys below the village of Puracé (2,648 meters) at an elevation of about 2,600 meters. These form the basement upon which is built the volcanic massive of Puracé. The height of the volcano above its foundation is thus about 2,000 meters, and its diameter at the base could be estimated at roughly 10 to 15 kilometers.

Dacite lavas of reddish color appear slightly inclined and in part lying almost horizontally, forming the lower part of the volcano up to an altitude of about 3,800 meters. They form a steep lava wall at the northwestern approach to the volcano. The truncated cone of Puracé above some 3,800 meters is made up of dark andesitic lava-flows interbedded with great amounts of andesitic tuffs, ashes, bombs and large blocks which form the pyroclastic cone of the volcano (fig. 2). Puracé therefore has a composite constitution. The dacitic shield volcano at its base is capped by an andesitic and pyroclastic cone. The andesitic lava-flows and tongues were apparently very viscuous and did not flow far from the crater despite the steep flanks of the volcano; the more recent flows were observed above 4,000 meters altitude.

On the northwestern side of the volcano and close to the main crater there appears part of a wall rising a little below the height of the crater rim. This may indicate the former cone of the crater or the wall of a parasitic crater that existed northwest of the present one. A small secondary crater is located

The southernmost sources of this great river originate, however, approximately 35 kilometers to the south at the Páramo del Buey, whence also descend the sources of Rio Magdalena, flowing to the east and Rio Patia, flowing to the south. This area of Colombia, where the largest river systems of the country originate, lies on a batholith of younger Tertiary age intruded into the older massive of the Cordillera Central. The volcanic range of Puracé as well as the active and dormant volcanoes of the region apparently represent magmatic outflows related to the rise of this batholith.

Rio San Francisco and Rio Vinagre descending from Puracé, both have deeply cut valleys. The valley of Rio Vinagre, which has its source at the cinder cone of the volcano, shows evidence of extensive mud-flows in its upper course. The waters of Rio Vinagre are highly sulphurous and according to some analyses carry over one percent of sulphuric acid and about one percent of hydrocloric acid. Several hot sulphur springs empty into the river. In its upper course the river bed is cutting thick sulphur layers at the foot of the volcano.

GLACIATIONS

Evidences of past glaciations around the volcano and on its lower flanks above an elevation of 3,500 meters are found in the form of typical U-shaped valleys, hanging valleys, glacier-polished surfaces and what might be remains of moraines. In the valley of Rio San Francisco glacial forms could be observed as low as 2,880 meters. This points to an intense glaciation that must have affected the whole range in Pleistocene times, and during the time that Puracé was most active. This confirms that Puracé is of pre-Pleistocene age.

Humboldt, at the beginning of the last century, as well as Reiss (1921) in 1869, described the range and particularly the peaks of Puracé and Pan de Azucar as being covered by an extensive snow cap. Likewise, within the memory of the old inhabitants of the region, ice and snow were carried by Indians to the town of Popayan for refreshment. Reiss, during his visit to the crater of Puracé, found about 70 meters of perpetual ice and snow on the crater's rim. But only patches of ice were reported at the top of the

of smoke on this occasion rose to about 1,000 meters. A few days before this, ashes and lapilli fell to a distance of more than 10 miles from the volcano. On May 26, 1949, there occurred an explosion, again with an earthquake and great quantities of ashes and bombs. The earthquake of June 11th which was experienced by the writer and his party was probably also accompanied by an explosive eruption. This, however, could not be observed due to dense clouds that enveloped the mountain.

From the sporadic, available data of the activity of Puracé over more than a century it would appear that the volcano has only slightly diminished its explosive character since the time of its first-recorded eruptions.

The lack of systematic observations, such as should have been carried out considering the nearness of the volcano to villages and towns, make it impossible at present to determine the periodicity of the eruptions as well as the exact evolution of the cone and crater. The writer's observations of April, 1947, as compared to those of Reiss of November, 1868, give interesting material for the study of the development of Puracé during the last eighty years.

REGIONAL PHYSIOGRAPHY

Puracé forms the northern peak of a high volcanic range of the Cordillera Central, known as Sierra de Coconucos; Reiss (1921) also called it the Puracé Range. The volcano lies some 85 kilometers south of Nevado de Huila (5,750 meters), the highest volcanic peak of Colombia, and 25 kilometers northeast of the conspicuous volcanic peak of the recently active Sotará (4,580 meters). Eighteen kilometers southeast of Puracé lies the symmetrical volcanic cone of Pan de Azucar (4,670 meters). This appears to be quite extinguished. The Puracé Range extends about 25 kilometers to the southeast, the southernmost peak of the range being Pico de Paletara (4,482 meters).

Puracé, therefore, forms the apex of a group of three volcanoes of which it is the only active one at present since Sotará and Pan de Azucar are latent or dormant. The Puracé Range together with the volcano Sotará to the west of it border on both sides the uppermost valley of Rio Cauca, the southeastern headwaters of which descend from the range.

region; the exact number of casualities was not recorded. The church of San José and many buildings in Popayan also were destroyed. A strong eruption of October 12, 1925, and a later one of November 5, 1925, are the first recorded activities of Puracé in this century. The observations were made by I. Friedlaender (1927) who also mentions another eruption of September, 1926, which was accompanied by flames and ashes. He observed the eruptions at a distance; his attempts to climb Puracé were, however, unsuccessful.

Subsequent eruptions were not recorded until April, 1946, when, according to the inhabitants of the village of Puracé, as related to the writer, a strong explosive eruption preceded by an earthquake shook the region, damaging the village church. The earthquake was felt also in Popayan.

The later recorded eruptions took place on April 27, 1947, when the writer ascended to the cratèr (fig. 1). The column

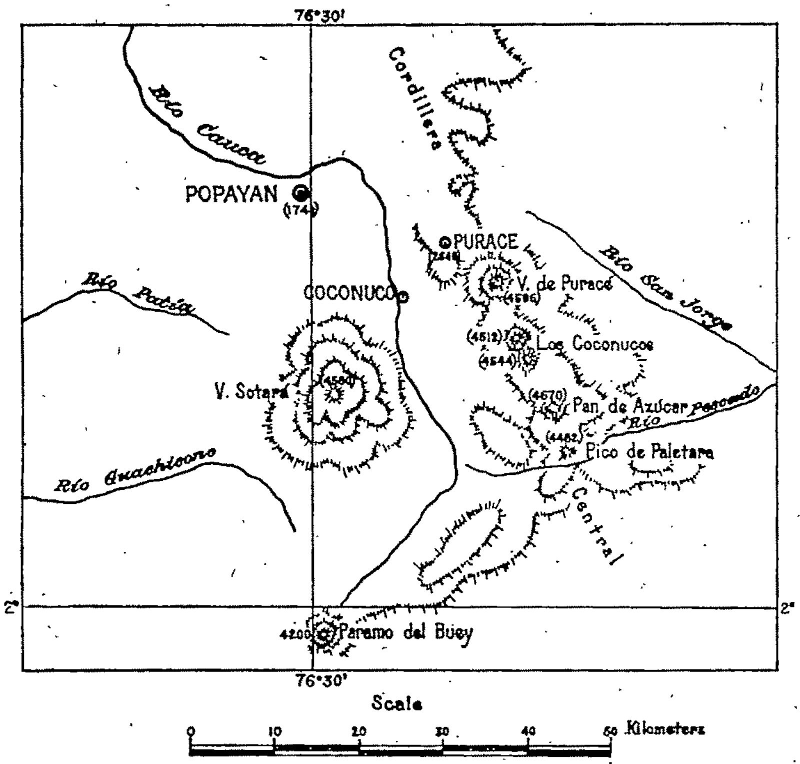

Fig. 1. Index map of Puracé Range, Colombia.

the region and the village of Puracé at a distance of about 10 kilometers from the volcano. Due to exceedingly bad weather conditions, rain and storm, and the danger of pyroclastic materials, the party had to return from an elevation of approximately 4,000 meters without reaching the upper part of the cone. Before this ascent on May 26th, a violent explosive eruption of Puracé, also preceded by local seismic shock, caused the death of seventeen students of the University of Popayan who were attempting to reach the cone of the volcano. On both occasions there were no flows of lava and the eruptions were accompanied only by outbursts of gases, steam, volcanic bombs and rocks; large rock fragments which fell from considerable height were responsible for the casualties.

HISTORICAL DATA

Although Puracé has existed as a volcano since Pliocene times and evidently was active during historical times, the first mention of Puracé's activity was made by Humboldt in 1801, and later by Boussingault in 1831. Neither of the two has, however, left a written or graphic description of the volcano.

One of the earliest eruptions of Puracé is mentioned by A. Stuebel as having taken place on November 18, 1827. From his travels in later years it appears that Stuebel had not succeeded in reaching the crater despite his persistent efforts.

Wilhelm Reiss (1921), Stuebel's companion, with whom he studied and described many volcanoes of Ecuador and Colombia, was the first scientist to describe Puracé and its crater, following his ascent of November 18, 1868. Reiss refers to a number of violent eruptions of Puracé between December, 1849, and 1852. After these eruptions it appears that the top of the mountain had been considerably lowered. According to Reiss (1921) the inhabitants fled from the neighboring village and the town of Popayan was covered with a blanket of ashes. Many small eruptions which occurred since have not been recorded. Reiss also describes an eruption of October 4, 1869, which was accompanied by an earthquake and large mud-flow. There were no further eruptions recorded until May 25, 1885, when, according to the memory of the inhabitants, a catastrophic explosion of Puracé accompanied by an earthquake killed many people and destroyed many houses in the

THE VOLCANO PURACE

VICTOR OPPENHEIM

ABSTRACT. The volcano Puracé (4,596 meters) in southern Colombia has been active within historical times. Despite its geological importance little has been mentioned of its development in geological literature. Thus far the only published record of scientific observations at its crater were made by W. Reiss in 1868. The studies of the writer during two visits to the volcano, in 1947 and 1949, provide additional and recent data.

Puracé is at present the only active vent of a group of Pliocene volcanoes at the northern edge of the Cauca-Patia batholith in the Cordillera Central of Colombia. The rise of this batholith could be related to the emergence of the Cordillera Oriental Geosyncline to the East. The group of formerly very active volcanoes, of which Puracé forms part, are obviously located on tectonic lines of crustal weakness of this part of the Andes.

The eruptions of Puracé are of explosive character. The ejecta are of andesitic nature. The upper cone is built of andesitic lavas, bombs, lapilli and ashes. The lower part of the volcano is, however, made up of thick flows of dacite. The total height of the volcano is about 2,000 meters above the crystalline basement of the Cordillera Central.

The periodicity of eruptions of Puracé could not be established; however, it still appears very active. The explosive eruptions are of an intermittent character and in recent times were not accompanied by lava flows.

INTRODUCTION

THE volcano Puracé in the Department of Cauca, Colombia, is situated some 30 kilometers S. E. of Popayan (1,741 meters) in the upper Cauca valley at about 2° 20′ Lat. N. and 76° 25′ Long. W.

The exact altitude of the top of the volcano was given by different authors as varying from 4,900 to 4,700 meters. The writer's observations with aneroid have shown only 4,590 meters above sea level.

The volcano was ascended by the writer first on April 27, 1947, and again an attempt was made on June 11, 1949; this time accompanied by the writer's wife and the French geologist, de Sakowetch. On both occasions the volcano was in a state of near activity. On April 27, 1947, an eruption was witnessed by the writer at 7:00 A.M., some six hours previous to his ascent to the crater. At this time a column of steam and smoke which reached about 1,000 meters above the crater was visible. Lapilli from 5 to 10 millimeters in diameter were projected to a distance of over 10 kilometers from the crater, and ashes covered the streets of Popayan.

On June 11th an earthquake lasting about 30 seconds shook

Virginia Pulp and Paper Company to carry on field work within their property, and also the co-operation extended by Mr. W. H. Knarr.

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Comparison with Windows Elsewhere in North America. Windows in major thrust sheets such as those in the Cumberland overthrust of Virginia (Butts, 1927), and the Bannock thrust sheet of Idaho (Richards and Mansfield, 1912) differ basically from the two windows here discussed. The windows of the Cumberland and Bannock thrusts are related to large low angle thrust sheets with displacements of tens of miles. However, the rocks exposed within the Birmingham and Knarr windows are not associated with such a large low angle thrust, and their present position is due to local synclinal folding and block faulting, later covered by a thrust which is low angle only within the area of the windows.

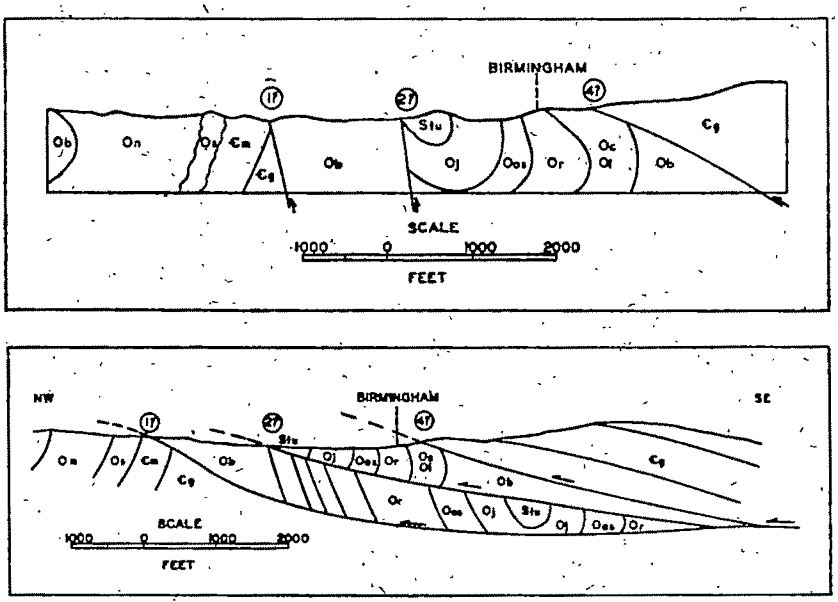

Figure 10. Structure sections across the Birmingham area, modified from Butts (1939). Upper section after Butts, lower section after Stose. For formational symbols see figure 2; for fault numbers (tentative) see figures 4 and 5.

ACKNOWLEDGMENTS

The author wishes to thank Professor Charles Merrick Nevin under whose direction this report was written. The writer appreciates the permission extended by Mr. Werden of the Pennsylvania Railroad and Mr. Little of the West

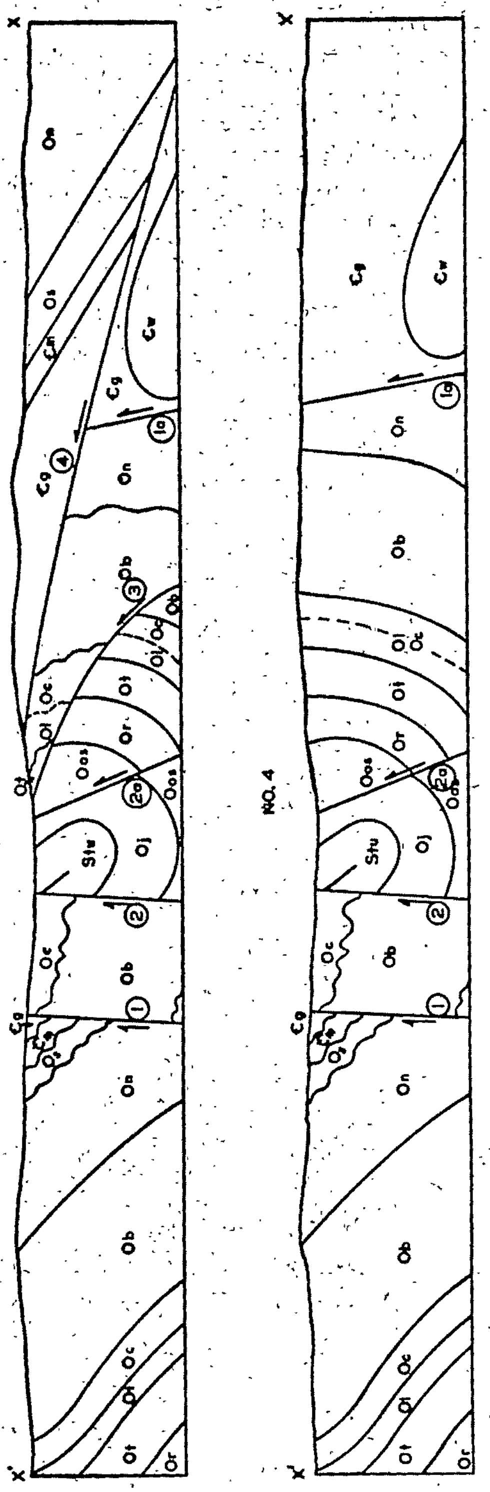

Figure 9. Schematic structure sections along line A-A', figure 4, showing last stages in the development of the Birmingham and Knarr windows. For formational symbols see figure 2.

tions have been brecciated, jointed and veined, even though there is no displacement of the Carlim-Bellefonte contact. This fracturing reflects the final absorption of the major faulting present at Birmingham. Sphalerite and galena mineralization is scattered throughout lower Sinking Valley, and is also present in the fracture zones within the windows. This mineralization has been structurally controlled and reflects the effect of major faulting at depth.

Comparison of Present Interpretation with Previous Interpretations. In Butts' paper (1939) two separate interpretations are set forth. The first of these is Butts' own interpretation which includes both a discussion and a structure section (fig. 10, upper section), and the second an alternative interpretation by G. W. Stose (fig. 10, lower section). Stose's section is based upon field data furnished him by Butts. At the conclusion of his interpretation Butts (1939, p. 78) says, "no fully satisfactory explanation of the entire situation has as yet been reached."

It is difficult from the discussion in Butts' paper to determine how he thought the windows were developed. It would seem that the major differences between the origin here proposed and the suggestions of Butts and Stose are:

(a) The size and location of the syncline. Both Butts and Stose would seem to require a major syncline that has been thrust a considerable distance from where it was formed. This interpretation makes it difficult to explain the rapid termination of the faulting to the southwest.

(b) The role of the Birmingham thrust. Butts and Stose thought that this fault was very large. In Butts' interpretation this fault must have a throw of about three miles; and all the faults in Stose's section are integral parts of a low angle thrust of large displacement. Here again a fault of this nature is contrary to the field evidence of the Birmingham thrust outside the area of the windows.

It would seem that a local syncline, later block faulted, would more nearly explain the present position of the formations exposed within the windows. This structure was overridden by the Birmingham fault, which was caused by the compressive forces that formed the southern half of the Nittany arch.

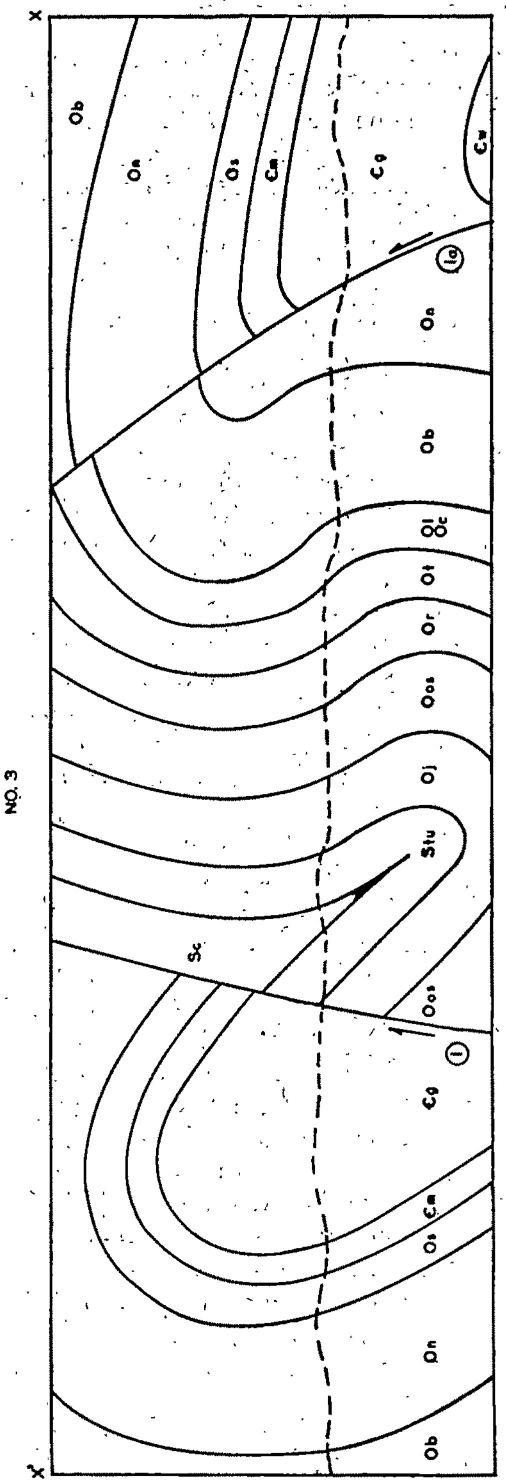

Figure 8. Schematic structure section along line A-A', figure 4, showing third stage in the development of the Birmingham and Knarr windows. Note change of scale from figure 7. For formational symbols see figure 2.

from the usual trend is partly caused by the strike slip displacement along a small transverse fault (see fig. 2). The bulge is limited to that portion of the flank opposite the windows. It would seem, therefore, that the conditions which brought about the structure exposed within the windows are of a local nature.

Development of the Windows. It is suggested that early in the development of the Nittany arch a local syncline was formed near the crest of this large arch (fig. 7, no. 1). This small syncline was overturned before it was faulted (fig. 7, no. 2), and its southeast flank is the Oswego-Juniata-Tuscarora sequence within the windows. It should be noted that the degree of overturning is the same as that of the major syncline between the axis of the Nittany arch and the Allegheny escarpment (both dip 35° to 45° S. 35° to 45° E.). Since this small syncline disappears southwest of Birmingham, it must plunge to the northeast, which is counter to the plunge of the Nittany arch. The resulting torque should have sheared and weakened the flanks. They failed, and a fault trough was formed. The bounding faults are thought to be high angle reverse faults as the graben was developed under active compression (fig. 8, fault 1 and 1a). At about the same time a smaller graben was formed within the larger graben (fig. 9, no. 4, faults 2 and 2a). Although for clarity these grabens are shown as though they developed separately, it is thought that they formed at about the same time. The faulted syncline was later overridden by two low angle thrusts (fig. 9, no. 5, faults 3 and 4). Fault 3 forms the base of a lower plate and is the older. The Birmingham thrust (fault 4) is the youngest and completely overrode the entire sequence. The thrusts were then slightly folded, and subsequent erosion has exposed the windows and uncovered the underlying structure.

Within the area of the two windows the strong rocks, the Oswego and Tuscarora sandstones, caused the Birmingham thrust to ride up and then across at a low angle. Outside this area, however, where the local syncline and infolded sandstones are not present, the sheet rode up against less interference. The change in the character of the Birmingham fault from high to low angle is paralleled by the change in trend of the west flank of the Nittany arch previously mentioned.

In lower Sinking Valley the Carlim and the Trenton forma-

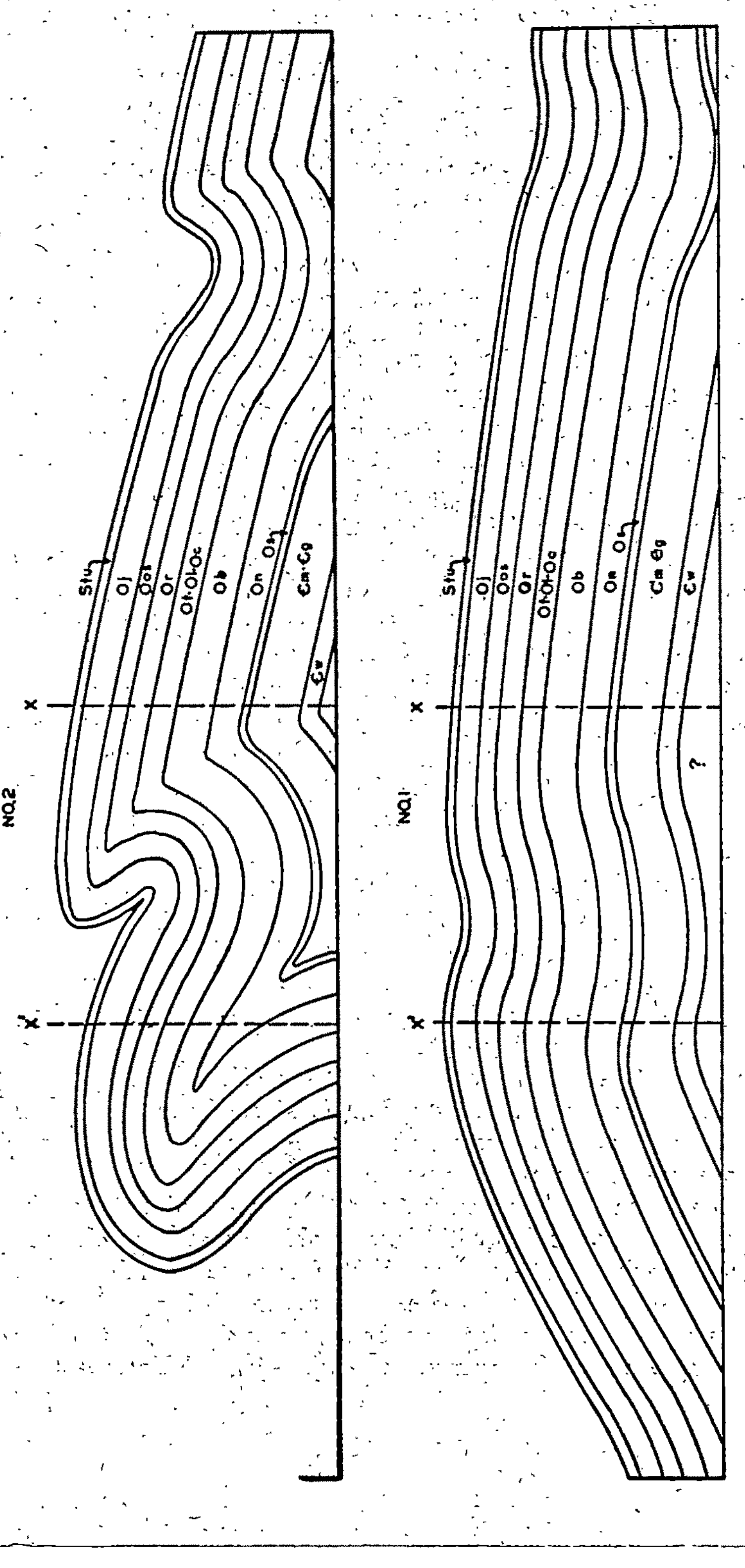

Figure 7. Schematic structure sections along line A-A', fig. 4, showing first two stages in the development of the Birmingham and Knarr windows. For formational symbols see figure 2.

same fundamental structure. Therefore, where field evidence was missing in one window it was supplied from better exposures of the same sequence within the other window.

ORIGIN AND DEVELOPMENT OF THE STRUCTURE OF THE SOUTHERN END OF THE NITTANY ARCH

The Nittany arch is the westernmost fold of the northern Appalachians, and is one of the largest structures of this province. To the west of this arch the beds of the Allegheny plateau are only slightly disturbed by folds of an entirely different nature. Price (1931) discussed the effect of a regional inherent weakness in the geosyncline as a controlling factor in the location and development of this arch. Even though it is over one hundred miles long and better than thirty miles wide, it is an overturned fold with some of the beds on the northwest flank dipping approximately the same direction and amount as those on the southeast flank. This fact places a large overturned syncline between the axis of the Nittany arch and the Allegheny escarpment to the west.

Along the crest of the Nittany arch is the Birmingham fault. This fault, except for the complicating factors exposed within the two windows, is a rather small thrust which has broken the arch at about its axis. At Stormstown (fig. 3) the stratigraphic throw of the Birmingham fault is about 2000 feet, and at Warriorsmark it is about 1800 feet. With the exception of the exposures within the windows, the throw decreases southwest of Warriorsmark until the fault disappears in Sinking Valley, along the plunge of the fold.

Within the two windows, the throw of the Birmingham fault suddenly increases to a maximum of some 8000 feet. However, as shown above, this fault is a relatively small thrust throughout the greater part of its length. Therefore, the problem is: Why does the Birmingham fault suddenly greatly increase its throw within the windows? The causes which brought this about should probably be local.

The extent of the structure within the windows may be related to two local peculiarities in this part of the Nittany arch. The first is the change of the Birmingham fault from a high angle to a low angle thrust in the area within and between the windows. The second is a bulge of the west flank of the Nittany arch to the northwest of about a mile. This departure

tions 1061 and 861 there is a reversal of the dip of the fault plane. The lower thrust (no. 3) has no complete reversal, but between elevations 855 and 857, a distance of 1900 feet, the dip of this fault is almost flat. However, between 857 and 1079, a distance of only 1100 feet, there is a marked southeast dip. Therefore, both of these thrusts have been warped by subsequent folding.

Fault 3, the lower of these thrusts, forms the greater portion of the northwestern border of the window. The rest of the window is bounded by fault 4, except for about 1000 feet bounded by fault 1. Actually the structure is a semi-window, rather than a true window, since no one fault completely surrounds it.

Faults 1, 2, and 2a are all high angle faults as shown by their outcrop patterns. Although there is no field evidence as to their direction of dip, they are thought to be high angle reverse faults.

The Knarr Window. A little over a mile northwest of Birmingham, along the axis of the Nittany arch, a smaller window is exposed. It covers an area 3800 feet long and 1900 feet wide. Since the Knarr farms lie near the center, it is here named the Knarr window (fig. 4 and pl. 1, fig. 3). The Gatesburg and Warrior formations enclose the window, and the Birmingham fault (fault 4) bounds two-thirds of it. The northwest side is framed by fault 1.

The Knarr and Birmingham windows are very similar. The same sequence, and also about the same thicknesses, of formations are found in both windows. Moreover, all of the faults are present in both windows. The faults in the Knarr window are numbered the same as their counterparts in the Birmingham window (figs. 4 and 5).

Two apparent differences in the exposures of the two windows should be noted: fault 3 is exposed for only 1000 feet along the southeastern edge of the Knarr window; and much less Carlim is exposed in the Knarr window than in the Birmingham window. These apparent differences are thought to be the result of greater warping of the fault planes of the two low angle thrusts (no. 3 and no. 4) in the Birmingham window, together with a greater amount of erosion of that window. Actually, there are no basic differences between the two windows, and they are merely separate exposures of the

feet southeast of Birmingham Station (pl. 1, fig. 1). Here, the lower Gatesburg is thrust over the Carlim, and the local dip of the fault plane is 15° to the southeast. Along the railroad northwest from this fault exposure there is 2850 feet of Carlim limestone. It is impossible to obtain significant dips within this distance as the Carlim has been badly folded and smashed. This Carlim cuts across the strike of the Oswego-Juniata-Tuscarora sequence observed in the section along the highway. That is, the Oswego-Juniata-Tuscarora sequence does not cross the river since it has been cut off by fault 3.

A small amount of Trenton limestone, less than 200 feet, appears before fault 3 is reached. Since the Carlim here again overlies the Trenton, it would seem that all the Carlim is overturned. The rest of the section along the railroad corresponds to the section previously described along the highway.

The Birmingham fault (fault 4) and fault 3 are flat, low angle, southeasterly dipping thrusts and are closely related in origin. An altimeter survey of the outcrops of these two faults shows that they have been folded (fig. 6). In the northeast portion of the Birmingham fault (no. 4) between eleva-

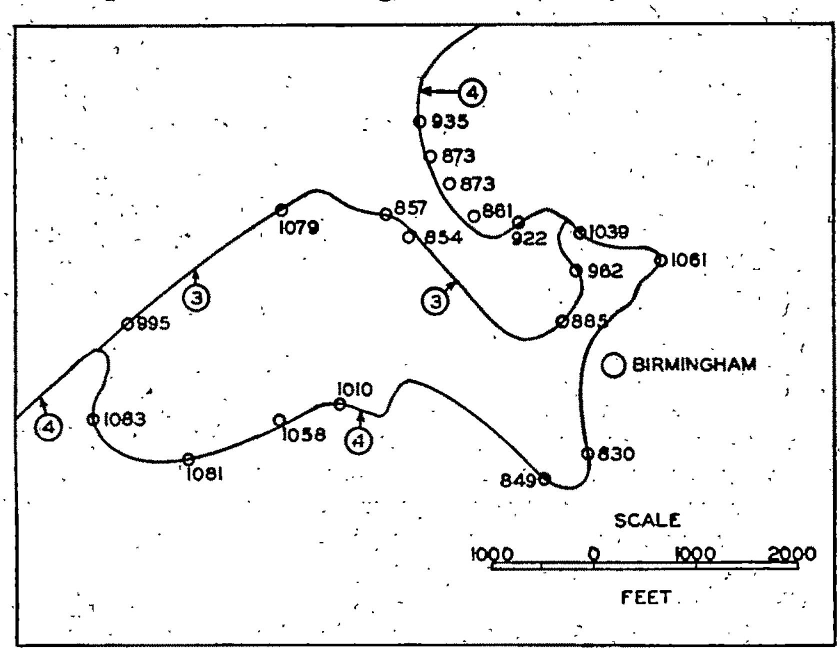

Figure 6. Elevations on the outcrops of faults 3 and 4 at Birmingham.

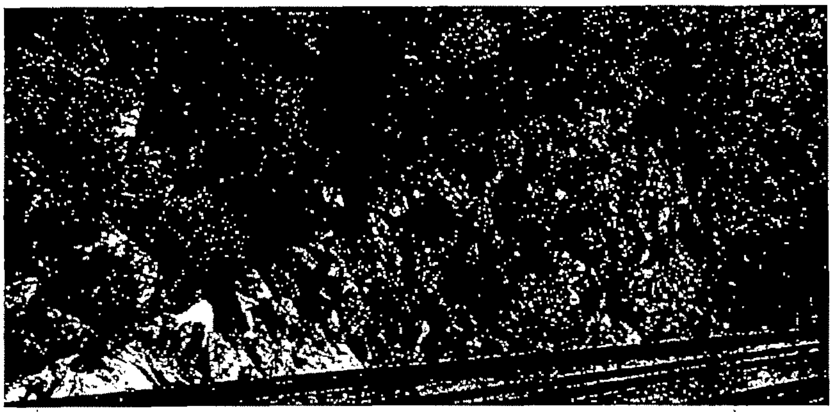

Plate 1, figure 1. Birmingham fault exposed along the main line of the Pennsylvania R. R. 1600 ft. south of Birmingham Station. The Gatesburg (dark colored) is thrust over the Carlim. View looking southwest.

Plate 1, figure 2. The Birmingham window (center) from Bald Eagle Mountain looking across the Nittany arch to the southeast.

Plate 1, Figure 3. The Knarr window looking north. The Warrior limestone forms the ridge in the foreground. The dashed line is the boundary of the window.

not present. There is 800 feet of Juniata exposed, and here the first significant dips may be taken. The Juniata dips 45° S. 40° E. Thus only 210 feet is left of the normal Juniata thickness of 1200 feet. The contact between the Juniata formation and the Tuscarora sandstone is gradational and normal. The Tuscarora dips 45° S. 40° E. The width of its outcrop is 480 feet, and, therefore, only 330 feet of the original 450 feet is exposed.

The window thus contains a sequence of overturned younger beds, all of which have been greatly reduced in thickness by shearing.

Bed rock is covered for the next 1200 feet by the flood plain of the Little Juniata River. This covered zone is terminated by outcrops of the Carlim limestone, just southeast of the Bald Eagle Water Co. pumping station. Here 50 feet of Carlim is exposed. The sequence of formations within the Knarr window, one mile to the northeast, indicates that this covered area may be underlain entirely by Carlim limestone, and it has been so mapped. If this is true the Tuscarora-Carlim contact is a fault (fault 2, figs. 4 and 5). This Carlim is the last formation within the window, and it is thrust against the upper Gatesburg.

Continuing northward along the highway, the Mines dolomite, Stonehenge limestone, and Nittany dolomite are all found in reverse sequence. The dips are to the southeast although, because of local folding, it is not possible to obtain a significant reading. The dip of the Nittany near the Nittany-Bellefonte contact is 35° S. 30° E. The Bellefonte is also overturned, and the reverse dip at about the center of the formation is 30° S. 45° E. From this point northwestward the beds slowly right themselves. The Carlim and Trenton still maintain a reversed position, the Trenton near the Reedsville contact dipping 75° S. 30° E. The Tuscarora beds are vertical at Tyrone.

Another important section through the Birmingham window is along the railroad cut of the Pennsylvania Railroad. This section is southwest of the river and roughly parallel to the main highway. Although the distance between these two sections averages only 300 feet, there is a surprising difference in the beds exposed.

The Birmingham fault appears along the railroad cut 1600

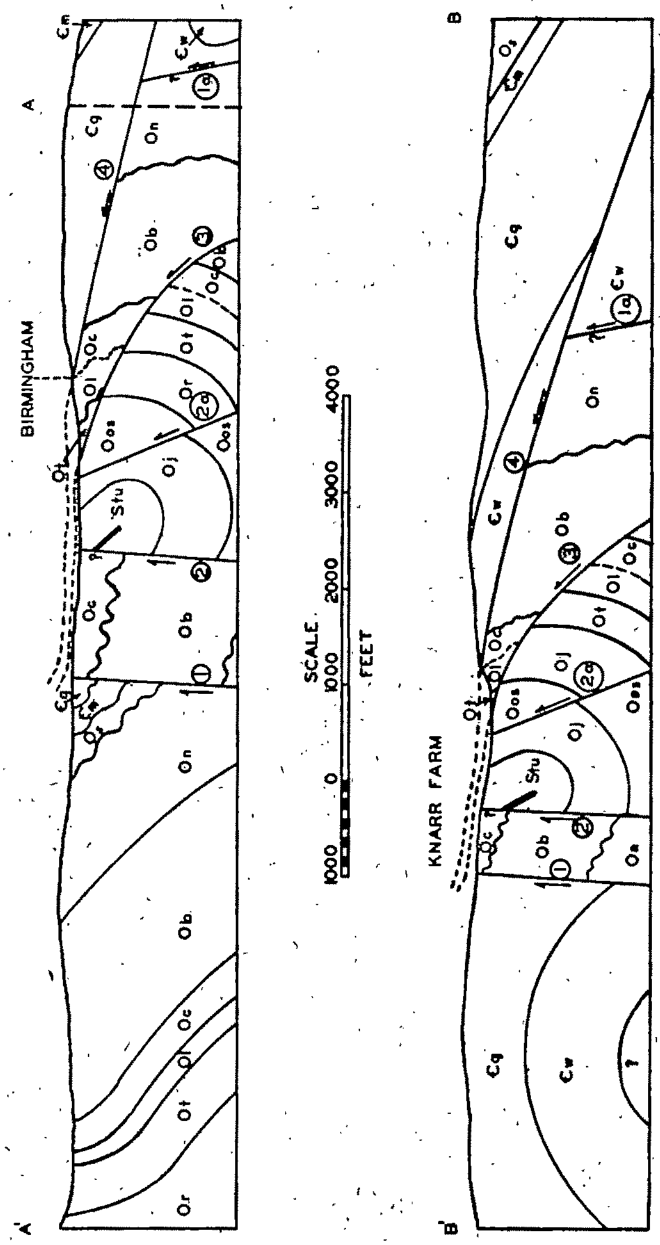

Figure 5. Geologic structure sections of Birmingham and Knarr windows, along lines A-A' and B-B' of figure 4. Faults numbered as in figure 4. For formational symbols see figure 2.

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THE JADEITE PROBLEM

PART I

HATTEN S. YODER, JR.

ABSTRACT. The literature is reviewed and new data on the jadeite problem are presented which redefine the probable stability range of jadeite. The mineral is known to occur in only three places: in Burma, as small masses in serpentine with albite or nepheline, or both; in Japan, also as small masses in serpentine with albite and quartz; and in Central America, but here no specimens have been found *in situ*. The interest in jadeite is due mainly to the theory that it is a high-pressure mineral. If a reaction is known to be possible on other grounds, it will proceed under pressure in the direction of smaller volumes. However, the mere fact that the supposed products are of smaller volume than the reactants is not sufficient basis for inferring that the reaction will take place. All attempts to synthesize jadeite, even at pressures up to 4000 atmospheres, have been unsuccessful.

Although no direct structure determination appears to have been made, the common assumption that jadeite has a structure similar to diopside is justified by an indirect method. It is suggested that the co-ordination of sodium is probably less than normally assigned and that the "excess" aluminum occupies silicon positions.

The temperature of formation is believed to be less than 800°C. since the mineral melts metastably at a temperature at least as low as 800°C.; it occurs with low temperature albite (<700°C.); it occurs in a reaction zone against serpentine (<500°C.); its chemical equivalents, nepheline + albite, appear to be stable in the presence of water down to 600° and 8000 atmospheres; and its glass fails to crystallize dry below 800°.

A new analysis of jadeite and data on the diopside—jadeite and acmite—jadeite joins are given. The jadeite problem is considered to be distinct from the eclogite problem.

INTRODUCTION

THE interest in jadeite, $NaAl(SiO_3)_2$, has arisen from a theory that it forms only under conditions of high pressure. At present jadeite stands as an example of a "high-pressure mineral" along with diamond and possibly the pyrope-almandine garnet. This view has been reached mainly from considerations of the eclogite problem since only one *in situ* deposit of jadeite has been studied in detail. The conditions of formation of the mineral jadeite have been considered analogous

to those of the rock eclogite even though the so-called jadeite molecule makes up only a small part, or even may be absent, in the eclogite pyroxene. These views on its formation are so firmly held that they are cited as evidence in the solution of earth structure problems. The purpose of this paper is to present new data which redefine the probable stability range of jadeite.

CHEMISTRY OF JADEITE

In 1863 Damour assigned the name jadeite to a mineral having the composition $NaAl(SiO_3)_2$. Since then it has been suggested that jadeite may constitute an important part of pyroxenes whose composition can be represented in terms of the end members acmite, hedenbergite, and diopside. These complex pyroxenes have been called omphacite, soda-augite, mayaite, chloromelanite, chromojadeite, lime-jade, fassaite, and others. The analyses of some 65 of these soda-alumina-bearing pyroxenes have been collected and their soda and alumina contents plotted in figure 1.

On first inspection one would conclude from the figure that there are essentially two different groups of jadeitic pyroxenes. However many of the analyses were made from artifacts such as jewelry and axe heads of both modern and ancient

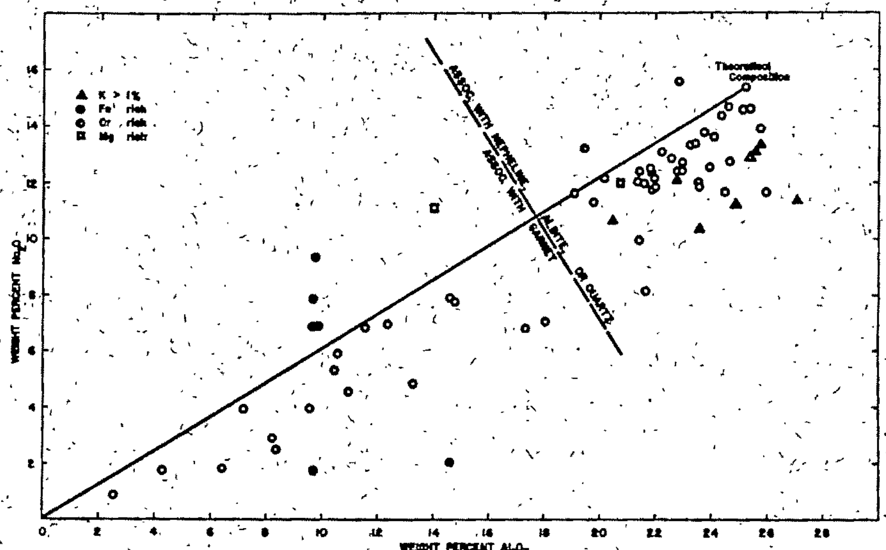


Fig. 1. Soda and alumina contents of complex pyroxenes.

civilizations. In addition many of the carved specimens may have been taken from the same boulder or fragment and therefore their analyses give undue weight in any statistical consideration. Others were made from impure pyroxenes separated from eclogites and other rocks. Most of the analyses were made around the year 1900. In spite of these shortcomings, the analyses show several interesting points. The group which most nearly approximates the ideal formula for jadeite are considered to be from only three distinct areas.

(1) Those specimens labeled as being obtained from Burma, China (Yunnan province), and Tibet are all believed to come from deposits in Burma. Many of the specimens from the Burmese localities were derived from a conglomerate, but for the past sixty years some have also been obtained from nearby *in situ* deposits. In order to avoid payment of royalties, according to Bleeck (1908), the Burmese jadeite had been smuggled across the borders to Yunnan, China, and to Tibet.

A locality was thought to exist near Karakash, Chinese Turkestan. This was also known as the Khotan or Kuen-Lung Mountain deposit. Musketov and Arzuni (Blagdanowitsch, 1892) believed that nephrite had been formed here at the expense of chloromelanite, but that no pyroxene was actually identified. In a personal communication, W. F. Foshag said no jadeite had been found in the specimens he had received from that locality.

Those analyses which contain a high percentage of potassium are said to come from China. It is not known whether these might not be from a particular boulder, containing orthoclase, which had been transported from Burma to China by man.

(2) A second locality, near the village of Kotaki, Niigata Prefecture, Japan, has been described in Japanese. Specimens have been received by the National Museum.

(3) A third locality is thought to exist in Central America (Oaxaca or Guerrero, Mexico, and Guatemala) where another conglomerate (Washington, 1922a), has apparently yielded boulders of jadeite. Neither the source of these boulders nor the original outcrop of jadeite has been found.

Another locality may exist in Switzerland, but it is more likely that the axes found were made from a single boulder erratic such as has been found in South Serbia (Tucan, 1929).

Without considering the archeological aspects of these localities, it can be said that there are essentially three deposits of a mineral which closely approximates the composition of jadeite. The important observation concerning these sources is that in each case jadeite is associated with nepheline or albite, or both. The remainder of the analyses are dominantly of pyroxenes taken from eclogites of various localities. In those cases the pyroxene is associated with a garnet. In figure 1 the straight line represents the ratio of soda to alumina calculated for the ideal jadeite. As has been pointed out by several writers, the alumina is generally in excess of that required for the ideal jadeite formula. This excess and the role of iron and magnesium will be interpreted on a structural basis in the following section.

STRUCTURAL ASPECTS OF JADEITE

In 1925 Wyckoff, Merwin, and Washington compared the spacings obtained from a diffraction pattern of jadeite with the corresponding lines of diopside. They found that the average spacings were some 3 per cent less than those for diopside. It was stated that jadeite has a similar pattern and therefore a closely related structure to diopside. The patterns were made on an unanalyzed sample from Middle America; the spacings were not published.

Of the monoclinic pyroxenes diopside is the only one for which a complete x-ray structure analysis has been made (Warren and Bragg, 1929). Warren and Biscoe (1931) state that from a comparison of augite, acmite, and spodumene, they "may reasonably conclude that diopside, hedenbergite, augite, clinoenstatite, acmite, jadeite, and spodumene are all monoclinic pyroxenes with diopside as the type structure." With the possible exception of spodumene they agree with the work done in 1925. It is to be noted that no diffraction patterns were made on a specimen of jadeite (this was confirmed in a personal conversation with Dr. Warren in 1948).

In 1932 Merritt published the lines for an unanalyzed specimen from "China." He said the pattern for jadeite is " . . . quite distinct from either diopside or acmite, although there is apparently a certain similarity."

In an attempt to resolve this difference of opinion, powder diffraction patterns were made of jadeite, acmite, diopside, and clinoenstatite on a recording x-ray spectrometer. The Geiger-

counter x-ray spectrometer (Norelco) was calibrated with a quartz standard using the following values:

hkl	2θ	d
100	20.876	4.2549 A.
101	26.664	3.3432
112	50.136	1.8177

The given d spacings are based on a weighted $CuK\alpha = (2K\alpha_1 + K\alpha_2)/3 = 1.5418$ A. Dr. L. H. Adams has shown that the Norelco instrument will consistently reproduce angles measureable to 0.02°. A nickel filter was used.

The jadeite from Burma (USNM #94829) has been analyzed with extreme care by E. G. Zies:

SiO_2	59.51	Na_2O	14.87
TiO_2	0.01	K_2O	0.02
Al_2O_3	24.81	FeO	0.03
Fe_2O_3	0.35	MnO	0.01
Cr_2O_3	0.01	P_2O_5	0.00
CaO	0.77	H_2O+	0.06
MgO	0.58		
		Total	100.08

This material had been examined optically by H. E. Merwin and found to be free of mineral inclusions. Dr. O. F. Tuttle was of the opinion that he had observed a sufficient number of liquid inclusions in a single thin section to account for the 0.06 per cent H_2O+ in the analysis.

The jadeite from Japan (USNM #105860) contained a large number of liquid inclusions in addition to tremolite and albite. Most of the included material in another piece of the same specimen was removed after grinding by centrifuging in Clerici solutions prepared by K. Neuvonen. The removed material after x-ray examination was identified as analcite by comparison with known patterns. No analcite was seen in the thin section prepared.

The acmite was from Quincy, Massachusetts, and has been described by Palache and Warren (1911). The material was taken from the same sample analyzed by Washington (Washington and Merwin, 1927).

The natural diopside was collected by F. E. Wright at Ham Island, Alaska, and its analysis is given by Allen and White (1909). The synthetic diopside was prepared by J. F. Schairer.

The clinoenstatite was taken from the material prepared by Bowen and Andersen (1914). The spacings smaller than 1.781 did not agree with those of Clark (1946).

A visual similarity was noted among clinoenstatite, acmite, and jadeite in both spacings and intensities. The intensities of diopside appeared to be unique among the group. This could have been anticipated from the much larger scattering power of the calcium with respect to the other atoms (except Fe). In order to compare jadeite more closely with diopside, whose structure is known, it was necessary to find a method of indexing its planes. Not having accurate unit cell data, it was assumed that the "c" dimension is approximately the same for all pyroxenes. Using the morphologically determined crystallographic ratios and beta angle of Penfield (Kunz, 1900), a reasonable unit cell size was calculated:

$$\beta = 72^\circ\ 44.5' \qquad 1.103 : 1 : 0.613$$

$$a = 9.45\ \text{A.}$$
$$b = 8.57$$
$$c = 5.25$$

An accurate check may be made on the dimensions of this unit cell. The volume of the cell, using the above values, calculated by the formula $V = abc \sin\beta$, is 406 A^3. The volume may also be determined using the formula $V = Mn/N_0\delta$ where:

M = molecular weight = 202.09
n = number of molecules in unit cell = 4
N_0 = Avogadro's number = $6.023 \pm 0.001 \times 10^{23}$
δ = density = 3.328 at 30.9°C. (Adams and Gibson, 1929).

This is equal to 403.28 A^3. It is concluded that the calculated unit cell dimensions are reasonable. The spacings for this assumed unit cell were calculated for most of the hkl's permitted in the space group to which diopside is assigned, C_{2h}^6, by the formula

$$d = \left(\frac{\frac{h^2}{a^2} + \frac{l^2}{c^2} - \frac{2hl\cos\beta}{ac}}{\sin^2\beta} + \frac{k^2}{b^2} \right)^{-\frac{1}{2}}$$

The calculated d's are listed in table 1 for comparison with those of the diopside from deKalb, New York. Those spacings for the deKalb diopside for which intensities are indicated were determined by Warren and Bragg (1929), the others were calculated. The pattern of the Burmese jadeite recorded

on film was taken and measured independently by A. J. Frueh for the purpose of comparing the two methods. It is seen that all the lines from the powder patterns can be assigned an index within the space group criteria. It appears as though acmite, jadeite, and clinoenstatite are pyroxenes having diopside as the type structure.

This specific problem can be approached in another way. If jadeite has the type pyroxene structure of diopside (XYZ_2O_6), a stable structure should result when Na and Al are substituted in the X and Y positions respectively. In diopside there are three distinct oxygen positions. The Pauling bond situation for these oxygens may be diagrammatically represented as in figure 2a. Here each bond is assigned a strength dependent on the charge and co-ordination of the atom in accordance with the Electrostatic Valence Rule (Pauling, 1929). It is seen that such an arrangement does not lead to a stable structure. Following the suggestion of Bragg (1937, p. 187), if two of the bonds co-ordinating the calcium atom to oxygens are assumed inactive, a stable structure results (figure 2b). In effect the bonding becomes that of clinoenstatite (YYZ_2O_6). To obtain the jadeite structure it should only be necessary to substitute Na in the calcium positions and Al in the Mg positions. Again assuming a six-fold co-ordination for the calcium position (as in spodumene and clinoenstatite) the bonding picture becomes that of figure 2c. This is not unreasonable for dominantly ionic structures, but a further improvement may be made. Buerger has made the suggestion that the co-ordination of the alkalies is, in general, too high. He postulated that sodium may have a co-ordination as low as four. Sodium has a co-ordination of four in Na_2O and also in the nepheline structure. For jadeite the bonding picture then becomes that of figure 2d. Such an analysis is limited by the fact that the bonds are not entirely ionic and that only the nearest neighbors are considered. However, it may be concluded that the assumed structure for jadeite is reasonable from the standpoint of bonding.

It is obvious that a more general picture must be considered than the simple substitution of sodium and aluminum in the proper positions. Warren and Biscoe (1931) have expressed the general formula for the pyroxenes as follows:

$$X_mY_{2-m}(Si,Al)_2(O,OH,F)_6,$$

TABLE 1

X-Ray Powder Diffraction Measurements of Diopside and Jadeite

C_{2h}^{6} hkl	Diopside deKalb, N.Y. d(Å)	I	Diopside Synthetic d(Å)	I	Diopside Ham Is. Alaska d(Å)	I	Jadeite Calculated d(Å)	Jadeite Burma-film d(Å)	I	Jadeite Burma-spec. d(Å)	I	Jadeite Japan-spec. d(Å)	I
110	6.45	0	N.O.		N.O.		6.21	6.19	4	6.18	1	6.18	1
200	4.68	0	N.O.		N.O.		4.52	N.O.		4.49	½	4.52	½
020	4.45	1	4.40	1	4.44	½	4.28	4.29	8	4.27	3	4.29	3
?	....	..	...	..	...	..	...	...	..	3.89	½	3.89	½
021	3.34	3	3.33	1	3.33	½	3.26	3.25	5	3.25	1	3.25	1
220	3.23	8	3.22	4	3.23	8	3.11	3.11	5	3.10	3	3.11	2
221	2.99	..	2.98	10	2.98	10	2.93	2.92	10	2.92	8	2.93	1
310	2.96	6	2.94	3	2.94	7	2.84						
311	2.89	..	2.88	4	2.89	1	2.84	2.82	10	2.83	10	2.84	6
130	2.84	½	2.79	½	2.82	½	2.73	N.O.		2.68	½	N.O.	
202	2.54	3	2.56	3	2.56	1	2.53						
002	2.53	10					2.51						
131	2.53						2.49	2.50	8	2.49	2	2.50	3
112	2.52		2.52	8	2.53	4	2.52						
$\bar{2}21$	2.51						2.43	2.42	8	2.42	9	2.43	2
$13\bar{1}$	2.41	..	2.39	½	N.O.		2.31	N.O.		2.31	½	2.31	½
400	2.33	1	2.29	2	2.29	1	2.25	2.24	6	2.24	½	N.O.	
040	2.22	0	2.21	1	N.O.		2.13	N.O.		N.O.		N.O.	
312	2.22				N.O.		2.21	2.19	6	2.20	2	2.21	½
022	2.19	5	2.19	1	2.18	½	2.16	N.O.		2.15	1	2.16	1
330	2.144	4	2.146	2	2.146	2	2.071	2.069	7	2.067	8	2.075	2
331	2.129	..	2.121	5	2.124	2	2.069	...	..	....	..	....	..
421	2.103	..	2.101	1	2.101	3	2.049	N.O.		2.043	1	2.046	1
420	2.076	2	N.O.		N.O.		1.999	N.O.		1.991	½	1.996	½
041	2.083	6	2.084	3	2.084	1	1.967	1.971	6	1.966	1	1.970	1

TABLE 1 (Continued)

X-Ray Powder Diffraction Measurements of Diopside and Jadeite

C_{2h}^{6}	Diopside deKalb, N.Y.		Diopside Synthetic		Diopside Ham Is. Alaska		Jadeite Calculated	Jadeite Burma-film		Jadeite Burma-spec.		Jadeite Japan-spec.	
hkl	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	d(Å)	I	d(Å)	I	d(Å)	I
240	2.017	1	N.O.		N.O.		1.934	N.O.		N.O.		N.O.	
$20\bar{2}$	2.012	6	N.O.		N.O.		1.959	N.O.		N.O.		N.O.	
402	2.010	6	2.008	2	2.002	3	2.002	N.O.		N.O.		N.O.	
241	1.948	..	1.954	1	1.959	½	1.888	1.892	3	1.887	1	1.893	½
511	1.892	..	N.O.		N.O.		1.842	N.O.		1.835	½	1.841	½
?	....	..	1.853	½	N.O.		1.768	....	..	....	..	....	..
510	1.836	4	N.O.		N.O.		1.810	1.761	5	1.760	2	1.763	1
422	1.833	..	1.828	1	1.830	½	1.683	N.O.		1.807	½	1.810	½
332	1.815	..	1.806	½	1.809	½	1.707	1.687	5	1.683	2	1.688	1
$42\bar{1}$	1.773	..	N.O.		N.O.		....	N.O.		N.O.		N.O.	
150	1.752	6	1.750	2	1.748	4	1.683	See 332		See 332		See 332	
$31\bar{2}$	1.711	..	1.720	½	1.680	½	1.662	N.O.		N.O.		N.O.	
042	1.668	5	1.670	1	1.668	½	1.629	1.623	2	1.623	½	1.626	1
313	1.657	..	1.656	1	1.655	½	1.657	1.656	2	1.652	½	1.655	½
441	1.627	..	N.O.		N.O.		1.579	1.577	6	1.570	4	1.574	2
223	1.623	..	1.620	3	1.622	2	1.616	1.613	2	1.608	½	1.610	1
440	1.612	4	N.O.		1.612	2	1.553	1.553	5	1.551	1	1.554	1
530	1.590	3	N.O.		N.O.		1.526	N.O.		1.523	½	1.526	½
023	1.584	½	N.O.		N.O.		1.576	See 441		See 441		See 441	
600	1.558	7	1.559	½	1.560	½	1.504	1.508	3	1.498	1	1.503	1
350	1.552	5	1.548	1	1.548	½	1.488	1.484	3	1.488	1	1.483	1
602	1.525	6	1.524	1	1.520	1	1.499	See 600		See 600		....	..

N.O. = not observed.

$I = I_{(hkl)}/I_{10}$

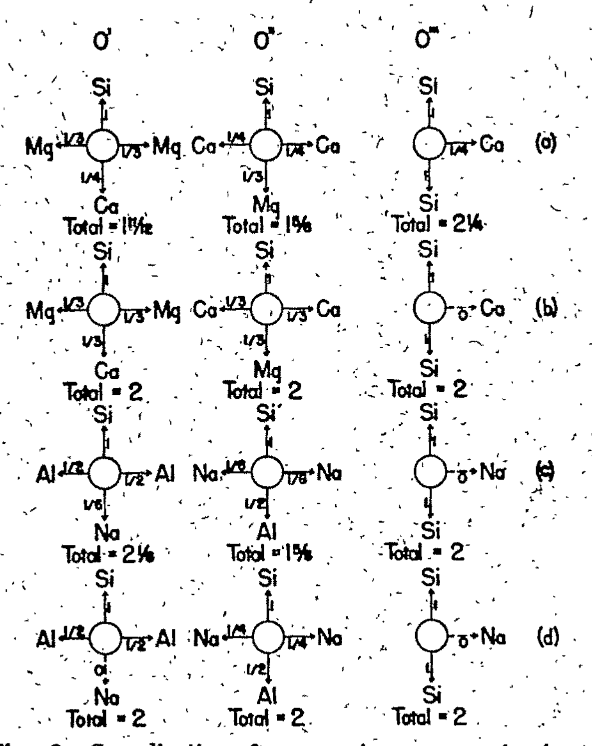


Fig. 2. Co-ordination of oxygens in pyroxene structures.

where X may be Ca, Na, K, Mn, and where Y may be Mg, Fe, Al, Ti, Mn, Li, and m tends to be either 1.0 or 0. Although there is insufficient data to define the limits, if any, of these substitutions, the following aluminous pyroxenes have been recognized:

Jadeite	$(Na,Ca)(\mathit{Al},Mg)(Si,Al)_2O_6$
Omphacite	$(Ca,Na)(Mg,Fe^{+2},\mathit{Al})(Si,Al)_2O_6$
Chloromelanite	$(Ca,Na)(Mg,Fe^{+3},\mathit{Al})(Si,Al)_2O_6$
Augite	$Ca,(Mg,Fe^{+2},Fe^{+3})(Si,Al)_2O_6$
Fassaite	$Ca(Mg,Al)(Si,\mathit{Al})_2O_6$

The groups as defined above represent only one opinion; the terminology is greatly in need of revision. The role of the "excess" alumina is that of a proxy for silica; an aluminum in a silicon position has a co-ordination of four. Warren and Biscoe further point out that as much as one-fourth of the silicon positions may be occupied by aluminum. In such a case the local bonding picture is satisfied if the atom in the calcium

position is allowed to change co-ordination as the situation dictates. Osborn (1942) has demonstrated that diopside can take up aluminum in its structure. It would be of great interest to learn the precise role of aluminum in such structures as fassaite. It is conceivable that the pyroxene structure may be controlled by activation or inactivation of some of the alkali bonds, or by the change in co-ordination of aluminum, or by both. How these changes may be brought about by changes in temperature or pressure are discussed in the following paragraphs.

The co-ordination of calcium is thought to be a function of temperature. According to Brandenberger (1936) and others, the calcium in Ca_2SiO_4 should surround itself with a smaller number of oxygens in the higher temperature forms. Bredig (1945) believes the higher temperature form to have its calcium in the higher co-ordination. The first view is based on the Goldschmidt Rule (1926) that at high temperatures that crystal structure is stable which could be obtained by substituting a cation having a greater electrostatic influence. The latter view is based on the argument that the weaker bond (Ca-O) becomes weaker, that is, the bond distance increases making greater co-ordination possible, before the stronger bond (Si-O) is affected. One would expect that the more loosely packed structures, for example, where the atom has the lower co-ordination, would exist at the higher temperatures. Buerger (1948, p. 115) also believes that there is a tendency toward lower co-ordinations at higher temperatures. He says that "Atoms in lower coordination are freer to wander over larger volumes, and thus have larger entropies." There is some reason, therefore, to believe that the co-ordination of the alkalies is a function of temperature.

Jadeite has most of its aluminum in the Y position (CN = 6) rather than in the Z (Si,Al) position (CN = 4). From geometrical considerations alone, it can be said that aluminum in six-fold co-ordination is in closer packing than when in four-fold co-ordination. In that packing is dependent on the ratio of the atomic sizes, it is therefore dependent on composition. This is shown strikingly by substituting the light weight NaAl combination in place of the heavier CaMg in the pyroxene structure; the density increases. In other words, if the composition is fixed, there exist limitations to the type of packing.

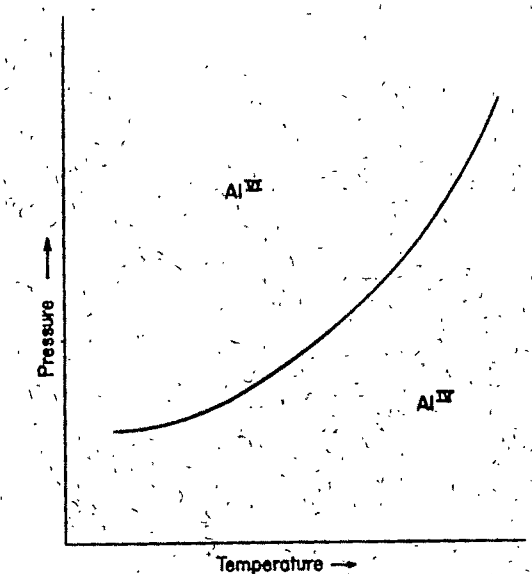


Fig. 3. Stable regions for different co-ordination of aluminum (after Thompson, 1947).

From a study of the chemical analyses, it appears that calcium throws aluminum into four-fold co-ordination and sodium throws it into six-fold co-ordination in the pyroxene structure. Other factors (*i.e.*, structural type) should be considered since in grossularite, for example, the aluminum is in six-fold co-ordination in the presence of calcium.

Wickman (1943) and Thompson (1947) consider the co-ordination of aluminum to be a function of pressure and temperature as shown in figure 3. (This shift in co-ordination is similar to the shift in co-ordination thought to occur in carbon as in figure 4.) Wickman, however, qualifies his statement by saying that in the presence of the strongly polarizing OH group the aluminum may also have six-fold co-ordination. Wang (1939) suggested that the co-ordination of aluminum was controlled by the amount of volatiles present. Of the soda-alumina-silicate minerals which have all their aluminum in six-fold co-ordination (glaucophane, tourmaline, and sodium montmorillonite, for example), only jadeite is considered to be anhydrous.

Much stress has recently been laid on the co-ordination of aluminum as a function of pressure. The concept of space conservation under high pressure can be traced back to the

Volume Law of Lepsius (1893, p. 191). The fact remains, however, that logically one cannot step directly from a minimum volume product to the agent of high pressure without intermediate considerations, *i.e.*, composition and temperature. These often overlooked considerations will be stated more precisely later in thermodynamic terms. Where the association is jadeite with albite or nepheline, or both, the aluminum is in both IV and VI. When the association is jadeite and garnet, the aluminum is dominantly VI. These two different types of association will be fully described in the following sections.

ASSOCIATION WITH NEPHELINE OR ALBITE, OR BOTH

Only one deposit, Upper Burma, has been studied where jadeite occurs *in situ* with albite or nepheline, or both. Noetling (1892) first described the deposits at Tawmaw (or Tammaw), Burma, as a vein in a black rock. Later (1893) he said the jadeite was intimately associated with an eruptive rock closely resembling serpentine. In 1896 Noetling finally concluded that the jadeite was either a separate intrusion into the serpentine or a cooling modification of the serpentine. The rocks collected by Noetling were described in detail by Bauer (1895). Bauer

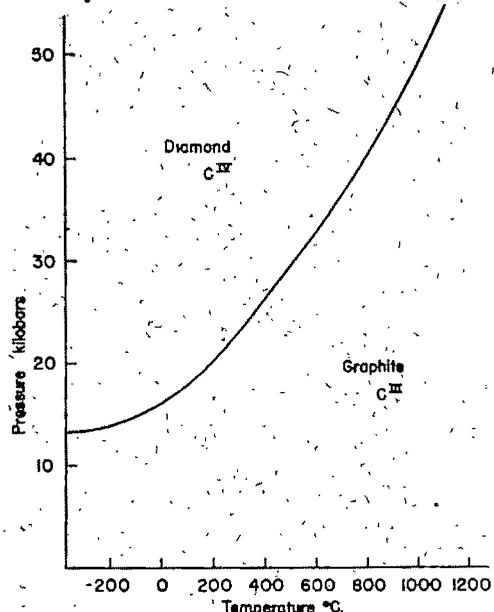


Fig. 4. Stable regions for different co-ordination of carbon (after Goranson, 1940).

thought that the Burma jadeite could not be considered an eruptive rock since jadeite had not been found in established eruptive rocks. Of particular interest is a fragment of a boulder, said to have come from Tibet, which Bauer (1896) described. In it were found jadeite, nepheline, and albite—locally one more abundant than the others. In one preparation needles of jadeite were completely enclosed by the nepheline; only small amounts of basic plagioclase were present. Bauer (1897) later said that the "Tibet" material occurred in a chlorite schist. In 1906 Pirsson and Iddings (Bishop, 1906, p. 162) described several specimens from Burma which contained either albite or nepheline. They considered the jadeite to be a constituent of a metamorphosed igneous rock (phonolite) and cited as evidence the cataclastic structure, the lack of (OH) bearing minerals, and the general absence in known igneous rocks. In the same year Bauer (1906) noted further in a specimen from Burma that jadeite occurred with plagioclase and contained needles of orthoclase.

In 1907 the deposit was again studied by Bleeck (1907, 1908) who described it as a broad dike in serpentine. Judging from the extent of the mines and quarries, the deposit was roughly 600 feet wide and 1500 feet long. A section through the dike is represented in figure 5. (The zone between the jadeite and serpentine was described by Noetling as "clayey soft serpentine." Later Chhibber (1934) described a similar zone as consisting of a crushed mixture of serpentine and jade-

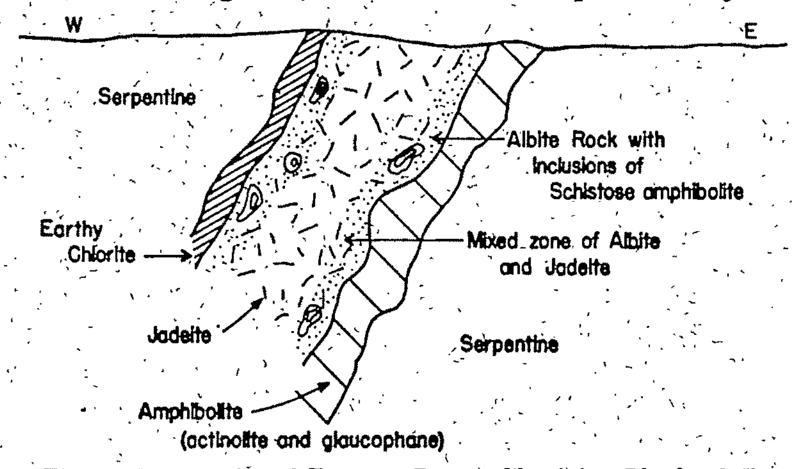


Fig. 5. Cross section of Tawmaw, Burma, dike (after Bleeck, 1907).

ite or amphibole in an irresolvable base.) Bleeck emphasizes the fact that albite is an important constituent of the dike. He says the intrusive nature of the dike is proved by the inclusions of the country rock and the veinlets of albite-jadeite extending into the country rock. Bleeck is of the opinion that the dike originally solidified as a nepheline-albite rock which later, under metamorphism at a very high pressure, was transformed into an albite-jadeite rock according to the equation:

nepheline + albite = 2 jadeite.

(The formation of jadeite by this reaction results in a 21.3% reduction in volume.) This follows the suggestion of Rosenbusch (1898, p. 508). The minerals developed in the wall rock are considered to be produced as a result of a reaction between the serpentine and the dike. This metamorphism was caused by a later intrusion of granite into the area.

Lacroix (1930) from his studies of Burmese specimens from museums and Chinese lapidaries came to the conclusion that the dike entered as a highly aluminous and sodic magma containing an excess of silica, stoping and metamorphosing its walls. Through desilication of the magma by the peridotite, the amphibolite zone was formed. The intrusion took place under high pressure, according to Lacroix, which permitted the production of minerals having the smallest volume, *i.e.*, jadeite.

A third field study was made of the Burma deposit by Chhibber (1934). His detailed examination of the mining operations and of many recently discovered outcrops in the jungle resulted in a picture somewhat different from that of Bleeck. The outcrops suggested to him that there are four dikes or sills intrusive into the peridotites and serpentines. The most recent workings in the Tawmaw dike (originally described by Bleeck) indicate that the jadeite occurs as large lenses from five to seven feet thick in the albite of the foot wall side. These lenses are separated by amphibolite, albitite, or an albite breccia. Chhibber believes the parent of the dike was a soda-granite-aplite which was a normal differentiation product of the granite magma which had penetrated the area. He postulated high pressure operating during the consolidation of the rock as the controlling factor, but also suggested that composition might be important. He notes that nepheline syenite is usually accounted for by desilication of albite; the intermediate compound could have been formed by a limited

desilication of albite. In general Chhibber agrees with the conclusions of Lacroix.

The authors agree that the source materials for the formation of jadeite are of igneous origin, and that pressure was the controlling factor. They disagree as to whether pressure was active during (piezocrystallization) or after (dynamometamorphism) the consolidation of the rock. Bleeck says that only the metamorphic reaction $Ne + Ab = 2Jd$ can account for the associations of $Jd + Ne$ and $Jd + Ab$. Lacroix points to densities as favoring crystallization under high pressure. These explanations must be regarded as speculations and not proofs for such processes.

It is true the association of jadeite with albite or nepheline, or both, has been found in only three localities; but it is to be noted that there are nepheline-albite rocks which do not contain a pyroxene, and, on the other hand, there are many such rocks which contain an acmitic pyroxene. The presence of iron also permits a mineralogy such as nepheline, sodic-pyroxene, and a garnet, as in the ijolites. Such an association may be the link between the nepheline-albite-jadeite rock and the garnet-jadeitic pyroxene rock.

ASSOCIATION WITH ALBITE AND QUARTZ

Very similar to the Burmese deposit is the jadeite deposit of Kotaki Village, Kubiki County, Niigata Prefecture, Japan (36°55′N, 137°50′E). Information on the deposit has been obtained mainly through the kindness of S. K. Neuschel, who, at the request of the writer, had a special report prepared by Helen L. Foster (1949). Information for the report and map was obtained from an interview with Schuichi Iwao, geologist for the Geological Survey of Japan, who has made detailed studies in the area. Two articles, published in Japanese, by K. Omori (1939), and by Y. Kawano (1939) have been translated in part by Dr. Joseph G. Hoshioka for the writer.

Jadeite was first discovered in 1938 in a block in the bed of Kotaki River. Kawano (1939) reported that a dozen and a half or so boulders up to several meters in diameter within a distance of 150 meters along the river were later found. He describes the jadeite deposit as being in a serpentine body, triangular in shape, bounded on the northeast by a fault against limestone, on the west by a conglomerate, and on the

south by sandstone and shale. The contact relationships were mostly obscured by talus and the actual exposures of the jadeite in place were not observable according to Kawano. Essentially the same relations were indicated by Kiyohiko Ishii who surveyed the region in 1932 (see Shiroumadake Sheet No. 136, Imperial Geological Survey of Japan). The mineral was described as occurring with actinolite and wollastonite and for this reason was thought to have been a product of contact metamorphism of the limestone. Omori (1939) also listed albite and tremolite as inclusions in the jadeite. It was not mentioned whether nepheline or quartz were present. Omori gave the indices of both the white and green jadeite as:

$\alpha = 1.658 \quad \beta = 1.668 \quad \gamma = 1.678 \quad c \wedge z = 38°$

Two chemical analyses have been made on the Japanese jadeite by Kawano:

	Theoretical	Green Jadeite	White Jadeite
SiO_2	59.44	58.02	58.35
Al_2O_3	25.22	22.96	23.90
Fe_2O_3		0.77	0.66
FeO		0.18	0.08
MgO		1.70	0.78
CaO		1.58	0.98
Na_2O	15.34	12.38	12.55
K_2O		0.16	0.12
H_2O+		0.87	1.24
H_2O-		0.61	0.67
TiO_2		0.04	0.04
MnO		0.01	0.00
Total	100.00	99.28	99.37

A thin section of the white jadeite with patches of green (USNM #105652) contained many inclusions both mineral and liquid. One vein cutting the section, about 0.1 mm. wide, contained a fibrous mineral of high index (approximately 1.60) and moderate birefringence. It is tentatively identified as tremolite. Being the dominant included mineral, the high H_2O+ in the analyzed jadeite could be accounted for by its presence in addition to the many liquid inclusions. It is to be recalled that considerable analcite was found in one sample. The details of the occurrence of the jadeite are quoted from the Foster report:

"The jadeite occurs with albitite and quartz. The so-called albitite is said to have a composition more like that of oligoclase

than of albite. Minor constituents of the rock include grossularite, actinolite, talc, muscovite, biotite, phlogopite, vesuvianite, zoisite, and hydrous wollastonite [xonotlite?]. No nephelite is associated with the jadeite. There are numerous occurrences of albitite which have no jadeite.

"The jadeite and associated albitite are found in rock composed principally of serpentine. In a typical occurrence, a central mass of albitite is surrounded by a series of concentric zones of different mineral compositions. The composition of the zones, from the innermost which surrounds the albitite to the outermost is (1) white jadeite which contains patches of green jadeite, (2) green jadeite, (3) actinolite mixed with green jadeite, (4) actinolite, and (5) serpentine. The width of the zones which contain jadeite vary from one-fourth of an inch to about two inches."

Four outcrops of jadeite were indicated by Iwao on a U.S. Army base map, three of which do not lie in the serpentine body as outlined by Ishii. This discrepancy cannot be accounted for at this time.

The similarity to the Burmese occurrence is striking; the main exceptions being the presence of quartz and the variety of minor constituents. Quartz as a major constituent immediately raises a question since quartz, albite, and jadeite cannot coexist under equilibrium conditions. Fermor (1938) suggested the following equation for the formation of jadeite from albite: albite = jadeite + quartz. This may well represent the case. There is, however, a consistent decrease in silica content from the albite core to the surrounding serpentine.

Some Japanese geologists believe the jadeitic masses to have formed from the residuum of a Mesozoic magma. Others have suggested that they resulted from contact metamorphism of the Paleozoic limestone.

ECLOGITES

A second type of association is a jadeitic pyroxene with garnet in the rock eclogite. Eclogite occurs only as lenses, masses, bands, or schlieren of small size in rocks of basic or ultrabasic composition. The structure is massive and the texture is described as granular and sometimes cataclastic. This picture is not unlike that of the nepheline-albite association. The eclogite is a bi-mineralic rock consisting of pyroxene, garnet, and a small amount of accessories. The pyroxene, usually called omphacite, is dominantly diopsidic and carries

small amounts of soda (0 to 8 per cent, average 4 per cent for 18 specimens) and alumina. The garnet is of the almandine-pyrope series and may carry appreciable amounts of grossularite.

A review of the literature from 1822 when Haüy (p. 456) first defined an eclogite indicates that there are six principal schools of thought on the formation of eclogites:

I. Direct crystallization from a magma under high hydrostatic pressure.
II. High-grade metamorphism of igneous or sedimentary rocks.
III. Metasomatism of sedimentary or igneous rocks.
IV. Dynamic metamorphism of pre-existing rocks.
V. Hydrothermal contact metamorphism.
VI. Migmatization or diatectic metamorphism.

The first two schools believe in the necessity of high pressure and high temperature for the formation of eclogites, but differ in the origin of the material. Most field workers are of this general opinion. The following is a composite of arguments, independent of area, which have been used by these workers.

1. The density (or high degree of packing) of the characteristic minerals and the rock as a whole suggest that an eclogite would occupy less volume under pressure than a gabbro of corresponding composition. This has been illustrated to be in accordance with the Le Chatelier principle by the reaction: augitic pyroxene + plagioclase = omphacite + garnet.

2. The elastic properties of the rock suggest that it is to be found in the deeper portions of the earth where high hydrostatic pressures and high temperatures are known to exist.

3. The occurrence of "fragments" of eclogite in the pipes of South Africa and Australia have been interpreted by some as evidence of a deep-seated source. (These first three arguments have given rise to the postulate that an inner shell of the earth consists of eclogite.)

4. Several field workers have noted that certain retrograde reactions have occurred in the eclogite, such as the formation of a diopside-plagioclase-symplectite, intergrowths

of hornblende and plagioclase, and "feldspar uralites" from the pyroxene. These have been thought to be due to the release of pressure.

5. The associated tectonites and accompanying "high-pressure minerals" have been cited as evidence. Diamond, rutile, kyanite, and other accessories have been named.

6. It has been recorded that the eclogite minerals are not known in established igneous rocks formed under "normal" conditions.

7. The eclogite minerals have not been obtained in synthetic melts at one atmosphere pressure.

8. The small size of the occurrences has suggested to some that the bodies are the result of "intense local conditions."

9. The massive structure and granular texture were used as criteria for high temperature and high pressure crystallization.

10. The presence of a pyroxene as well as the lack of OH minerals was considered as evidence for high temperature conditions.

The above "criteria" for the formation of eclogite at high temperatures and high pressures have, of course, not stood without questioning. The following, in corresponding numerical order, are some of the objections raised against each of the above arguments.

1. High density in itself is not conclusive evidence that a reaction proceeded in a given direction under pressure; temperature and composition must also be considered. A simple analogy may be found in the statement that a reaction may go if the heat of reaction is negative; here the criterion should be free energy. In addition Wagner (1928) says that eclogites and basalts are not chemical equivalents.

2. Diabase and dunite have elastic properties similar to eclogite. Since diabase may also form near the surface, these properties cannot be conclusive evidence for deep-seated formation.

3. Many consider the "fragments" as "segregations" in a normal magma. Some agree that the "fragments" are carried up from depth, but that they are from an ancient metamorphosed complex whose conditions of formation can no longer be traced. Korjinsky (1937) concludes from the

absence of eclogite in the pre-Cambrian that it originated only at moderate depths.

4. The alleged retrograde reactions have also been interpreted as up-grade reactions; that is, the "inclusions" are relics. Even the "unmixed" pyroxenes of Hentschel (1937) may be due to normal magmatic processes.

5. The nearby tectonites have in some cases been shown to be produced after the formation of the eclogite. In some areas the associated rocks include limestone and shale. The existence of "high-pressure minerals" has yet to be proved.

6. The line between an igneous augite bearing a little soda and an omphacite is not very sharp. Garnets approaching the composition peculiar to eclogites have been found in skarn zones.

7. Not all the tricks of crystal growth have been employed in the attempted production of the eclogite minerals.

8. It has been suggested, in at least one area, that the small masses are remnants of much larger bodies. The large lenses, and dike-like bodies are border-line cases.

9. Massive structure and granular texture have also been assigned to low-grade metamorphism by some writers.

10. Diopside, the dominant portion of an eclogite pyroxene, is considered to be one of the first minerals to form in the metamorphism of a dolomitic limestone. Many writers have indicated that pyroxene is not a mineral critical to any particular set of conditions. Several field workers have reported the presence of zoisite, hornblende, mica, and others as primary minerals in the eclogite.

Almost every worker has based his conclusions on observations in only a single area, yet the freedom with which these interpretations have been applied to other areas is unusual, and only a few workers seem willing to concede that eclogites may form in more than one way. Although the division of thought into sharply delineated schools is a matter of convenience, the writer believes the following workers may be regarded as belonging to the first school of thought: Wang (1939), Eskola (Barth, Correns, Eskola, 1939, pp. 366-367), Harker (1932, pp. 307-308), Williams (1932, pp. 316-353), Waldmann (1929), Eskola (1921), Wagner (1914, p. 130), Ktenas (1907), Holland (1900, p. 245). In the second school of thought it is probably correct to list Davidson (1942),

Fermor (1938), Sahama (1935), Briere (1920), Stillwell (1918), du Toit (1908), Holway (1904). Another group of writers supporting the high-pressure, high-temperature schools are either non-commital as to the source of materials or suggest both sources as being possible: Turner (1948, p. 106), Baker (1945), Holmes (1936, p. 379), Eskola (1936), Alderman (1936), Ernst (1935), Tilley (1936), Adams and Gibson (1929), Eskola (1920), Fermor (1913), Clough (1910, pp. 32-35), Grubenmann (1910, p. 228), Hezner (1903), Rosenbusch (1898, p. 508).

The third principal school is of the opinion that eclogites are produced by the metasomatism of sedimentary or igneous rocks. Hentschel (1937) interpreted the eclogites of Gilsberg as a secondary product of a reaction between pneumatolytic or pegmatitic solutions and a peridotite. The resulting pyroxenite "unmixed" to give an eclogite pyroxene and garnet. Ghosh (1941) considered the charnockite series of Bastar State and Western Jeypore, in which eclogite occurs, as complexly metasomatized impure calcareous sediments rich in iron and magnesium. The chief criticism that has been raised against this last view is that it fails to explain "the world-wide association of basic charnockite and eclogite with anorthosite" (Davidson, 1942). Groves (1935) specifically states that no anorthosite is associated with the charnockite series in Uganda. Düll (1902) believes the eclogite of Munchberger to be the result of metasomatism of gabbro-norite by a "hot, acid bath" from a granite.

Another school of thought adheres to the view that the materials were subjected to the processes of dynamic metamorphism. Groves (1935) considers this to be the dominant factor while Eskola (Barth, Correns, Eskola, 1939, pp. 366-367), Backlund (1936), Kranck (1935), Waldmann (1929), Eskola (1921), and Hezner (1903) consider it only a contributing factor. Kranck, in particular, has presented a detailed account of the mechanics of the process. He cites the following evidence: rolled-out character of the bodies, rotational whorls in garnets, broken schistosity, mechanical mixing of eclogite minerals with surrounding gneiss, and the parallel arrangement of other minerals.

A fifth school is represented by those who consider the small bodies of eclogite to be a product of contact metamorphism:

Saranchina (1946), Switzer (1945), and Korjinsky (1941). Saranchina describes eclogite and amphibolite in which are preserved "armoured" fragments of gabbro-norite. The eclogite-amphibolite series is said to be produced where the gabbro is in contact with migmatite or pegmatitic veins. Switzer describes the formation of glaucophane schists through hydrothermal contact metamorphism by serpentine intrusives. In view of the intimate association in the field, he concludes that the eclogites were formed nearly contemporaneously and through the same genetic process. On the basis of chemical composition he believes the eclogite to be derived from basalt. Korjinsky considers talc deposits which were partly nephritic and possibly jadeitic to be formed where borders of "desilicified pegmatites" are in contact with hyperbasites and feldspar rocks. A deposit of similar mineralogy was reported near Mt. Vernon, Skagit County, Washington (Zodac, 1939), but the presence of jadeite has not been clearly established (personal communications from S. L. Glover, J. W. Melrose, and C. D. Campbell, 1948).

Still another school of thought believes that migmatization or diatectic metamorphism produces eclogites. This process is supported by Weiseneder (1937), Fiedler (1936), Weiseneder (1936 and 1932), Heritsch (1926), Fersman (1925), and in part by Backlund (1936) and Kranck (1935). Backlund relates the formation of eclogite to the passage of the migmatite front. He believes from his study in Greenland that the highest temperatures and extreme dynamic pressure give rise to the true eclogite. Fiedler explains the eclogite of Erzgebirge as a "particular metamorphic condition" in the amphibolite. Pre-existing materials have been affected by the "diatectic" process, *i.e.*, "pegmatitic solutions under high pegmatitic pressures." Weiseneder considers the eclogites to be the result of progressive thermal metamorphism under the influence of residual solutions from a local magma. He further notes that at the same time as this extreme metamorphism at depth there was a material exchange within the metamorphosed series.

It has been hoped from this rather lengthy review of the eclogite problem that some clue to the synthesis of jadeite could be found, but it seems as though eclogite has been considered to be formed by all known major geological processes pertaining to igneous and metamorphic rocks. It is the opinion

of the writer that the small amount of soda commonly found in the eclogite pyroxene does not justify the assignment of special extreme conditions for its formation. The well-established fact that specific bulk compositions may yield different mineralogies under slightly different environments does not require elaboration. The diopside-grossularite skarns should enjoy equal popularity under the criteria listed in the above arguments. In fact Weiseneder (1932) has used the term pseudoeclogite to describe such skarn deposits. Because of the apparently ubiquitous occurrence of the eclogite pyroxene and its low soda content, the eclogite problem is considered to be separate and distinct from the jadeite problem.

RELATION OF JADEITE TO ANALCITE

The formation of analcite, $NaAlSi_2O_6 \cdot H_2O$, is to be considered in that its composition is similar to jadeite. Being much different structurally, analcite should not be referred to as "hydrated jadeite." The secondary occurrence of analcite in vugs and cavities is well known. Its primary occurrence in basic rocks, although debated for many years (Scott, 1916), is apparently now accepted. Analcite has been observed as an alteration product of jadeite. The relation of analcite to nepheline and albite has been represented by the following: nepheline + albite + $2H_2O$ = 2 analcite. (Assuming a density of one for water, the formation of analcite results in a 2 per cent increase in volume.)

The analcite dikes of Quebec (Adams, 1913, p. 45) suggest that a magma existed which was capable of providing the materials to yield jadeite. The fact that some of the analcite crystals in the dike contain idiomorphic inclusions of sodic pyroxenes, nepheline, and albite is noteworthy. These brief notes are only to draw attention to many occurrences which might be regarded as potentially jadeitic.

An early suggestion was that jadeite could be produced by dehydrating analcite. Gruner (1928) heated a crystal of analcite to 700°C. and found no change in structure. This was verified by Taylor (1930) who also noted slight changes of intensities of reflections owing to the loss of the H_2O contribution. On heating at 1000°C. analcite breaks down into nepheline and albite. The relations of analcite to nepheline and albite will be treated in detail in the following sections from both a theoretical and experimental point of view.

(To Be Continued)

STRATIGRAPHIC STUDIES IN NORTHERN PERU

BERNHARD KUMMEL

ABSTRACT. Detailed measured sections of Permian, Triassic, Liassic, Neocomian, and Aptian rocks are described from the Cordillera Central, Cerro de Caya Caya, Departamento de Amazonas, Peru. The stratigraphic data presented are the bases for extensive faunal studies on the Triassic and Permian which are now being carried on. The Permian section is the most northern fossiliferous Permian section so far reported and its fusulinids indicate an early Leonard age. This is also the youngest Permian studied in Peru to date. The Triassic rocks contain the only ammonite fauna of that age yet discovered from Peru.

INTRODUCTION

WHILE in the employ of the Peruvian Government in the old Departamento de Petróleo, Cuerpo de Ingenieros de Minas* the author had the oppórtunity to make some stratigraphical studies in the Cordillera Central of northern Peru between the Maranón and the Utcubama Rivers. Fine sections of Permian, Triassic, Liassic, Neocomian and Aptian rocks were studied and measured in detail on the west flanks of the Cerro de Caya Caya. Steinmann (1929) had visited the area and made note of these formations including a limited discussion of some of the contained faunas. The main objective of this study was to measure and collect the unique fossiliferous Triassic rocks which crop out over a large area in the Utcubamba Valley. A preliminary report giving the stratigraphic data obtained is presented here.

The fusulinids from the Permian section were studied by T. G. Roberts (1949), and they establish well the age of these beds. Large collections from the Permian and the Triassic are in the process of study. A part of the Triassic fauna has been described by Jaworski (1922). The Triassic fauna is noteworthy in that it represents essentially the only ammonite

* The duties of this organization are now incorporated in a new agency, the Establecimientos Petroléros Fiscales, Ministerio de Fomento. The support and encouragement for this study by Sr. A. Cabrera La Rosa, Gerente of the above organisation is gratefully acknowledged. The writer is grateful to Sr. Fernando Neri for his companionship and able assistance in the field. The writer also wishes to express his appreciation to C. O. Dunbar for preliminary studies on the fusulinids and to T. G. Roberts who studied and published a description of this fauna.

fauna of that age yet recorded from Peru. The fossils are silicified; approximately a ton of fossiliferous blocks of this Triassic limestone has been etched so far yielding thousands of specimens representing protoconchs to mature individuals. The fauna also contains pelecypods, gastropods, ostracods, brachiopods, and sponge spicules. This fauna represents part of the large Peruvian Triassic collections at the American Museum of Natural History, New York City, that is being studied by Newell, Haas, and the author (Science, 1947, vol. 106, p. 144).

LOCATION OF THE AREA

The Cerro de Caya Caya is part of the Cordillera Central of the Peruvian Andes and is situated on the divide between the Maranón and Utcubamba Rivers. The area of study lies entirely in the Departamento de Amazonas in northern Peru. This Departamento fronts on the great Amazon rain forest all along its eastern border. The western boundary lies well in the Cordillera Central and parallels more or less the upper course of the Maranón River. There are no roads connecting this area with the coastal regions of Peru. Under an old road building program there was projected a road from Balsas on the Maranón to the town of Leimibamba on the Utcubamba River over the Cerro de Caya Caya; however, only three kilometers were completed and those out of Leimibamba. The traveler wishing to visit the region can enter over well used and ancient mule trails that start at several points west of the Departamento de Amazonas. At the present time there is a weekly air service from Chiclayo on the coast to Chachapoyas, the capital of the Departamento. One of the most used mule trails starts at Celendin in the southwestern part of the Departamento de Cajamarca and climbs to a high divide at approximately 3000 meters above sea level directly east of Celendin; the trail follows a winding descent to Balsas on the Maranón River, at 900 meters, then begins to follow a circuitous route to the summit regions of the Cerro de Caya Caya at approximately 3700 meters; and then follows the descent to the town of Leimibamba on the Utcubamba River which lies approximately 2200 meters above sea level. The stratigraphic sections described in this report were measured for the most part along this mule trail between the summit regions

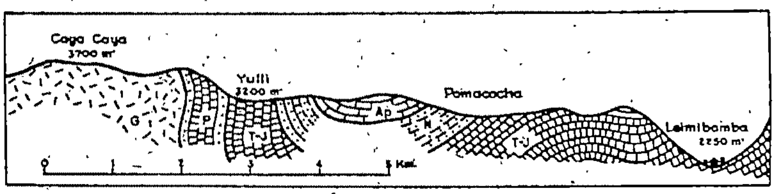
of the Cerro de Caya Caya and the town of Leimibamba. Along this sector of the trail are two valleys. The first above Leimibamba is called Pomacocha and here the Triassic and Jurassic rocks outcrop the best; the second, higher up the mountain side is called Yulli. The high northern walls of Yulli valley are formed by Neocomian and Aptian rocks; the southern walls are formed by Permian, Triassic and Jurassic rocks.

The author entered the region by flying to Chachapoyas and proceeded from there by mule to Leimibamba, with a stop over at Suta. The sections around the Cerro de Caya Caya were worked for the most part out of Leimibamba. The return trip with all the fossil collections was made with 18 mules following the trail from Leimibamba to Celendin and took three days.

STRATIGRAPHY

General Relations. The outcropping rocks of the region have a regional NW-SE strike and are in general strongly folded and faulted. The core of the Cerro de Caya Caya is pink granite overlain disconformably by Permian rocks. In the area between Caya Caya and Leimibamba the rocks are only slightly faulted and have broad open folds (Text fig. 1); however, between Leimibamba and Chachapoyas the Triassic and Jurassic rocks are badly faulted and folded. Along this latter stretch it is difficult to measure any complete sections. No conclusive evidence was obtained of the nature of the contacts between the various formations. Most contacts were seen in only small locallized outcrops. However, there is no reason to believe that any angular discordances are present.

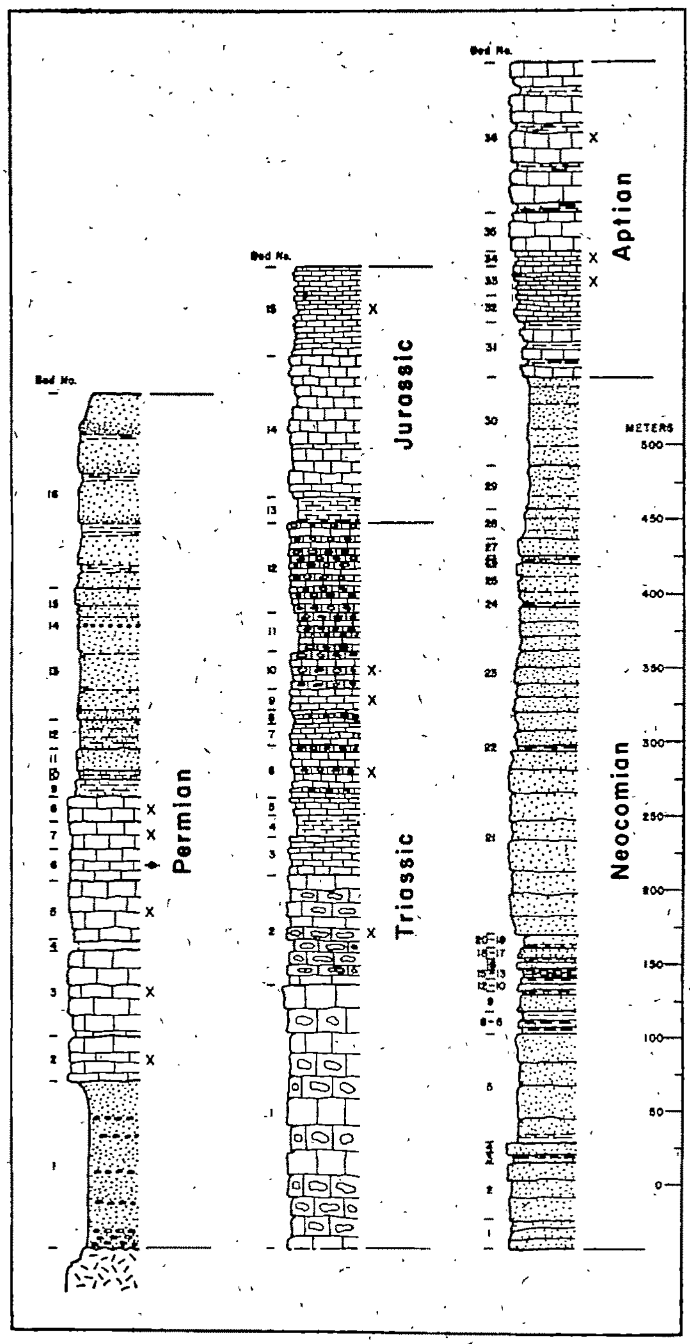
Permian. Directly overlying the pink granite forming the



Text Fig. 1. Section showing structural relations of formations between the Cerro de Caya Caya and Leimibamba (after Steinmann, 1930). G — Granite, P — Permian, T-J — Triassic-Jurassic, N — Neocomian, Ap — Aptian.

core of Cerro de Caya Caya are 589 meters of rock assigned a Permian age. The Permian sequence is composed of three main lithologic divisions. There is a lower basal conglomerate, arkose, and sandstone member predominantly red in color and 115 meters thick. This is succeeded by a thick massive limestone sequence containing myriads of silicified fossils. The fusulinids came from bed 6 (Text fig. 2) 258 meters above the base of the formation. This limestone member is 210 meters thick. Overlying the limestone member is a series of red to brown sandstone, clay-shale, and siltstone which is overlain by Triassic limestones. Fusulinids are present only in bed 6 and were identified by T. G. Roberts (1949, p. 236-238) as *Parafusulina Kummeli* Roberts; they indicate an early Leonardian age for the enclosed strata. This Permian sequence appears to be the youngest Permian section thus far recorded in Peru. Dunbar and Newell (1946) record several sections of Wolfcamp in central and southern Peru and from Bolivia (Text fig. 3). The abundant fusulinids in their strata show very close similarities with the Wolfcamp of West Texas (Dunbar and Newell, 1946). These authors give a fine summary of the present knowledge of the Permian rocks of Peru and Newell, Chronic, and Roberts (1949) have undertaken a more extensive study of the Upper Paleozoic rocks of Peru. Thompson and Miller (1949) have described several fusulinid faunas from Venezuela and Columbia and show the occurrence of Permian rocks younger than any so far reported from Peru. These authors also give an excellent summary of the previous work on South American fusulinids.

Triassic. Triassic rocks outcrop extensively along the Utcubamba valley between Chachapoyas and Leimibamba, where they have been named the Utcubamba formation by Weaver (1942). Above Leimibamba along the mule trail to Celendin in the region of Pomacocha, the Triassic rocks are very well exposed. Half way between Chachapoyas and Leimibamba is a small tributary of the Utcubamba River coming in from the east called Suta, where Steinmann obtained the silicified ammonite fauna studied by Jaworski (1922). A fine silicified fauna was obtained from the Suta locality at several distinct horizons. Unfortunately, however, the area is strongly faulted and no top or bottom of the section could be found. The section recorded here was measured at Pomacocha above Leimibamba.



Text Fig. 2. Columnar sections of formations measured between the Cerro de Caya Caya and Leimibamba.
X — fossiliferous horizons -●- fusulinid horizon.

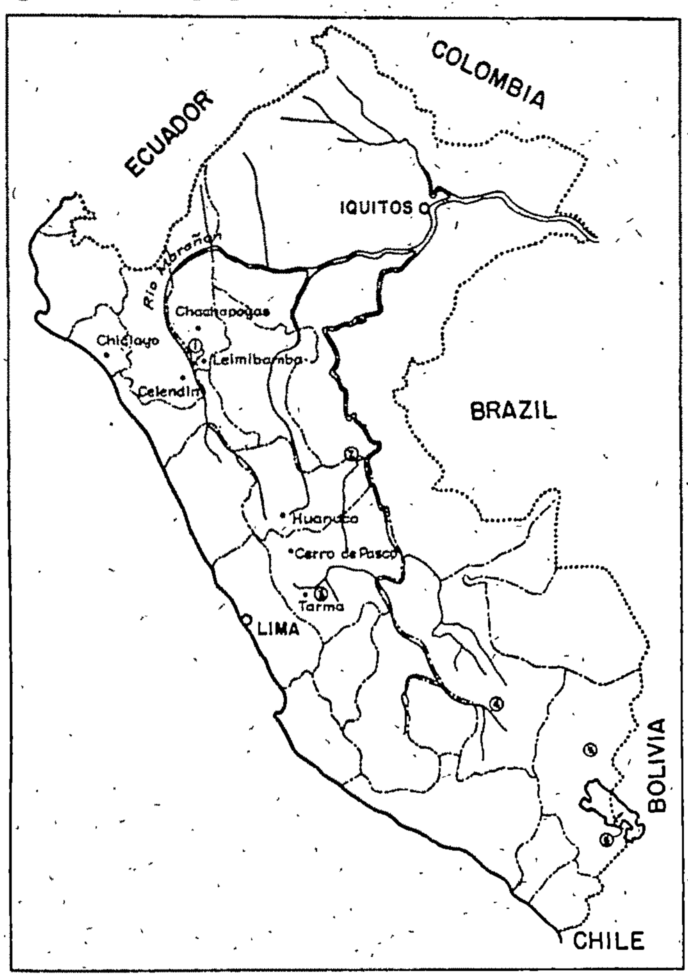
Permian section measured in Cerro de Caya Caya, along trail between Leimibamba and Balsas and above Yulli Valley; November 7, 1945.

Triassic limestone

Massive cliff of gray, thick-bedded, silicous limestone.

Permian	Thickness (in meters)
16. Sandstone, yellow-brown, conglomeratic in parts, with granite boulders, some interbedded red sandstone and shale beds, micaceous, mostly covered	132.00
15. Sandstone, red and yellow-brown, interbedded with brick-red silty shales, micaceous	24.00
14. Sandstone, red, conglomeratic with boulders of granite, micaceous	2.00
13. Siltstone, gray-brown to tan, massive, weathers yellow-brown on surface, contains thin interbedded units of red micaceous siltstone, partially covered	63.00
12. Siltstone, red micaceous, massive and laminated, partially covered	20.00
11. Sandstone, gray-brown, fine-grained, massive, partially covered	15.00
10. Siltstone, brick-red, clayey, micaceous, thin-bedded, partially covered	6.00
9. Sandstone, gray-brown, micaceous, medium-grained, both laminated and massively bedded, soft, partially covered	12.00
8. Limestone, gray, compact, massive, with myriads of silicified fossils	18.00
7. Limestone, brown, weathers iron-brown on surface, massive, with chert concretions, myriads of silicified fossils	18.00
6. Limestone, gray-black, compact, hard, massive, weathers light-gray on surface, contains fusulinids (*Parafusulina Kummeli* Roberts) and other silicified fossils	21.00
5. Limestone, gray and brown alternating, massive, partially covered, contains silicified fossils	42.00
4. Covered, interval occupied by stream bed	11.00
3. Limestone, brown, compact, crystalline, very massive, forming first prominent scarp past the granites, weathers dark-gray, contains myriads of silicified fossils, productids and crinoid stems the most abundant	60.00
2. Limestone, gray, finely crystalline, compact, with chert concretions, weathers dark-gray, contains myriads of silicified fossils, crinoid stems, brachiopods, etc., partially covered	30.00
1. Conglomerate, arkosic, cobbles and boulders of quartz and dark igneous rock, massive, interbedded with thick zones of red medium-grained sandstone, soft, containing some pebbles of quartz; this unit outcrops in a grass-covered and partially covered zone between the granites and the first massive limestone scarp	115.00
Total	589.00

The Triassic is composed of thick massive gray limestone in the lower part with thinner bedded units towards the top. The whole section contains abundant chert concretions and many units are very silty. Silicified fossils are present almost throughout the whole section. However, due to transportation problems only the more apparent richer beds were sampled. Jaworski (1922) assigned a Norian age to the Suta fauna listing the following species:



Text Fig. 3. Map showing location of known Permian sections in Peru. 1. Cerro de Caya Caya, 2. Ganso Azul discovery well, 3. Yauli formation of Dunbar and Newell (1946), 4. Cerro Pirhuate, 5. Munani section, Quebrada Quishurani, 6. Straits of Tiquina.

Nevadites Lissoni Jaworski
Nevadites Sutanensis Jaworski
Anolcites Dieneri Jaworski
Sagenites aff. *quinquepunctalus* Mojs.
Rhabdoceras curvatum Jaworski
Placites op. cf. *Sakuntala* Mojs.
Monophyllites sp.
Arcestes sp.
Metasiberites annulosus Mojs.
Pseudomonotis ochotica Keys.
Nucula aff. *carantana* Bittner
Leda sp. cf. aff. *sulcellata* Muenst.
Cardita cf. *singularis* Healy
Pseudoscalites subornatus Jaworski
Eucycloscala cf. *exigua* Healy
Dentalium sp. cf. *simile* Broili

The collection on hand includes all of Jaworski's species and several more; too little work, however, has been done as yet to make any additional statement about the age of the fauna. The fauna contains predominently ammonites, with small numbers of gastropods, pelecypods, brachiopods, bryozoa, ostracods, and sponge spicules. The gastropods are being studied by Haas in conjunction with his study of the gastropod fauna from the Triassic rocks of the Cerro de Pasco region of central Peru. The pelecypods are being studied by Newell and the ammonites by the author.

This Triassic fauna is unique in that no other Peruvian and few other South American localities have yielded such an abundant ammonite fauna from Triassic rocks. The Utcubamba formation contains *Pseudomonotis ochotica* which is an Upper Triassic Norian species with a world wide distribution. It has been recorded from Norian rocks in Siberia, Alaska, Japan, Nevada, California, Oregon, Columbia, Ecuador, Peru, New Zealand, New Caledonia, the Indian Archipelago, and in the Crimea. In Peru (Text fig. 4) *Pseudomonotis* has been recorded at Huaira in the Chinchao valley northeast of Huanuco (Steinmann, 1929), near Concepcion and Tarma (Harrison, 1940), at Carhuamayo and Cerro de Pasco (Boit, 1940, 1945), and just north of Olmos, east of the Sechura desert in northern Peru (A. A. Olsson, personal communication). *Pseudomonotis* is recorded from the basal part of the Santiago formation in eastern Ecuador (Tschopp, 1945, 1948).

Triassic-Jurassic Limestone measured at Pomacocha, along trail between Leimibamba and Balsas, October 29, 1945.

		Thickness (in meters)
Liassic		
15.	Limestone, black, bituminous, thin-bedded, slabby, brittle with large limestone concretions, lithographic in part, interbedded with some dark-brown calcareous shaley siltstone, few fossils present	60.00
14.	Limestone, gray, regular and massively bedded, mostly covered; some drag folds and reverse dips present in this part	96.00
13.	Shale, gray-brown, calcareous, interbedded with 25 cm. to 50 cm. beds of brown silty limestone, partially covered	18.00
	Total	174.00
Triassic		
12.	Limestone, gray-black, regular but wavy bedded, with much chert concretions, weathers tan and gray, very hard, no fossils	62.00
11.	Covered, on opposite side of valley appears to be the same as above	26.00
10.	Limestone, gray black, regularly bedded, cherty, contains silicified fossils, mostly covered	26.00
9.	Limestone, dark-gray, massive, compact, contains silicified fossils in several distinct horizons, also with scattered fossils throughout	15.00
8.	Limestone, dark-gray, compact, weathers tan and light-gray on surface, contains bands and rounded masses of chert, bedding irregular	9.00
7.	Limestone, dark-gray, weathers gray and tan, silty, in irregular beds 25 cm. thick, weathers in pitted and streaked surface	14.00
6.	Limestone, dark-gray, in wavy beds 20 cm. thick, with frequent 25 cm. to 50 cm. beds of chert, weathers light-gray, contains some silicified fossils, upper part partially covered	36.00
5.	Limestone, dark-gray, compact, hard, in beds 25 cm. thick, alternating with thin units of tan silty marl	12.00
4.	Covered, shaly and thin-bedded limestone	14.00
3.	Limestone, gray, in even regular beds 25 cm. to 50 cm. thick	26.00
2.	Limestone, tan, hard, compact, weathers gray, contains abundant chert concretions, massive in beds 1 to 2 meters thick, contains some silicified fossils	75.00
1.	Limestone, steel-gray to blue-gray, extremely massive, forms principal scarp in Triassic-Jurassic section, contains abundant hard chert concretions, also chert beds, limestone hard, compact, weathers gray, no fossils seen	180.00
	Total	495.00

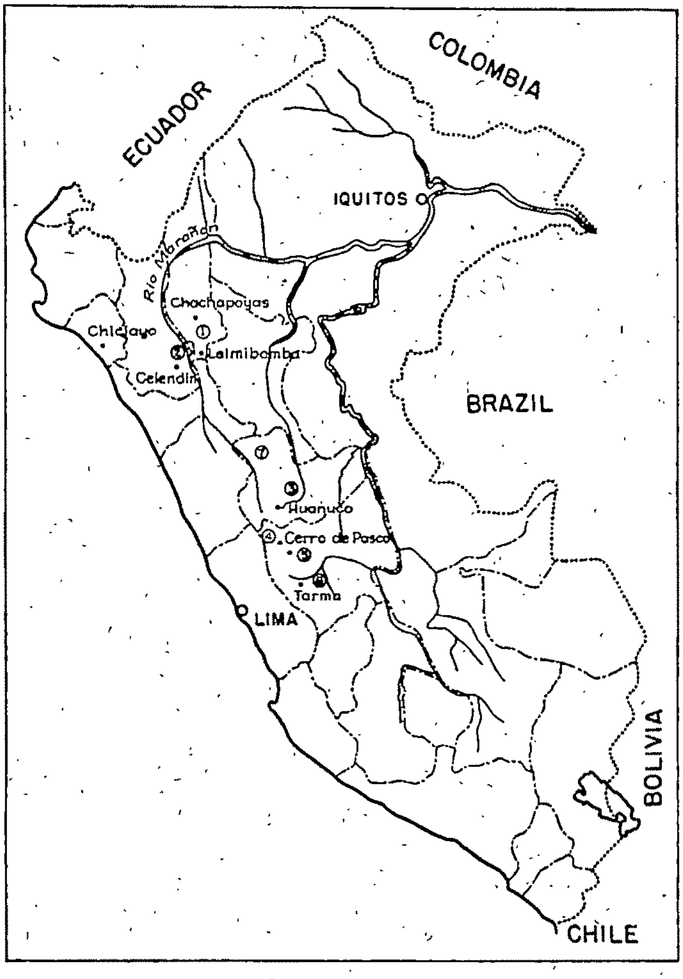
The small scattered outcrop areas of the Peruvian Triassic include strata of Ladinian, Karnian, and Norian age. No Skythian, Anisian, or Rhaetic rocks have as yet been recorded from Peru. The Ladinian is represented in a limestone sequence in the Cerro de Acrotambo (Korner, 1937). The Norian limestone of the Cerro de Pasco region has been reported frequently; however, this rock sequence has not been well documented by stratigraphic and paleontologic data (W. F. Jenks, personal communication). The distribution of the Norian rocks has been referred to above. It is hoped that the present paleontological studies being carried on with the extensive Peruvian Triassic material at the American Museum will add greatly to our present meager knowledge of the Triassic of Peru.

Liassic rocks: The oldest Jurassic rocks outcropping in Peru are found in the Utcubamba valley. Numerous isolated exposures of these rocks can be seen between Chachapoyas and Leimibamba; however, structural complications make the measurement of detailed stratigraphic sections very difficult or impossible. Overlying the cherty Triassic limestones at Pomacocha, above Leimibamba, are 170 meters of black limestone and calcareous shales assigned a Liassic age. Unfortunately no fossils were found in this particular region.

Steinmann (1929) recognized Hettangian and Sinemurian rocks in the Utcubamba valley. Weaver (1942) named the Hettangian rocks the Chilingote formation and the Sinemurian rocks the Suta formation. The Chilingote formation consists of dark limestones, dolomitic in part, and calcareous shales and the Suta formation consists of thin-bedded limestones and interbedded shale beds. In the Pomacocha section it appears that bed 13 (Fig. 2), and part of bed 14 belong to the Chilingote formation whereas the remainder of bed 14 and bed 15 belong to the Suta formation. Bed 14 contained structural complications and was too covered to be accurately subdivided in the field.

Cretaceous. Sandstones of Neocomian age are well exposed along the mule trail from the intermountain valley of Pomacocha to Yulli. The trail ascends at a rapid rate following a very circuitous route and in many places over the more friable and softer sandstone units is more than six feet deep, having been worn down through the constant passage of mules and horses over a long period of time. The rocks assigned a Neo-

comian age are 589 meters of coarse to fine-grained, heavily cross-bedded sandstone with much shale interbedded. They overlie Jurassic limestones; the contact conditions were not observed but appear to be conformable. The sandstone is for the most part in very massive units, white to gray-white, and usually weathers yellow-brown on the surface. The sandstones contain abundant thin lenses and scattered masses of quartz pebbles, very characteristic of the Neocomian in many other



Text Fig. 4. Map showing location of principal Triassic outcrop areas in Peru. 1. Suta, 2. Cerro de Caya Caya, 3. Chinchao valley, 4. Cerro de Pasco, 5. Carhuamayo, 6. Concepción and Tarma region, 7. Cerro de Acrotambo.

places in Peru. Throughout the whole section there are numerous thin clay shale beds. Some of the shale beds are laminated with fine-grained sandstone and contain abundant mica flakes and plant fragments. The shale beds are more numerous in the lower half of the formation. No plant material well enough preserved for identification was found. The upper part of the Neocomian sandstone forms a broad terrace upon which rests a thick sequence of Aptian limestone.

Neocomian rocks have a very wide distribution in Peru. Their distribution in Peru has been well summarized by Weaver (1942). Lower Neocomian rocks are continental sediments in eastern and central Peru; along the coast in the vicinity of Lima these beds contain some marine members also. The Barremian (Upper Neocomian) in many places in central Peru is composed of shales and limestones containing marine fossils. The Neocomian rocks of the Caya Caya region are considered to be at least partly correlative with the thick Lower Cretaceous sandstones of Central Peru (McLaughlin, 1924; Weaver, 1942, etc.) and to the lower part of the Oriente formation of eastern Peru (Kummel, 1946, 1948).

Overlying the Neocomian sandstone are 212 meters of light-gray limestone, argillaceous in part. The lower half of the formation is in thin-bedded, partly shaly units; the upper part is heavy, massive, gray limestone beds having a conchoidal fracture. Throughout the sequence fossils are scarce and poorly preserved. These rocks are assigned an Aptian age on stratigraphic position only and may even include some Albian rocks.

Lower Cretaceous section measured at Yulli, along trail between Leimibamba and Balsos, November 8, 1945.

Aptian	Thickness (in meters)
36. Limestone, light-brown to tan, compact, hard, massive, with conchoidal fracture, forms huge scarp, has some 1 to 2 meter shaly marl beds, fossils throughout but few and poorly preserved	100.00
35. Limestone, gray-brown, massive, forms prominent scarp, some fossils present, weathers gray on surface	27.00
34. Limestone, light-gray, thin-bedded, hard, with conchoidal fracture, weathers tan and gray on surface, some fossils present	10.00
33. Limestone, gray, argillaceous, in regular beds 10 cm. to 25 cm. in thickness, contains poorly preserved pelecypods, echinoids, weathers grayish tan	20.00

	Thickness (in meters)
32. Limestone, light-gray, argillaceous, shaly and thin-bedded, weathers tan on surface	18.00
31. Covered, probably argillaceous limestone, shaly, exposed in part on other side of syncline	37.00
Total	212.00
Neocomian	
30. Covered, unit very soft, forms low platform beneath Aptian limestone	60.00
29. Sandstone, white-gray, fine-grained, massive and soft, contains much carbonaceous material and plant fragments	30.00
28. Sandstone, white and yellow-brown, fine-grained, and black shale units laminated and thinly bedded, contains mica flakes and plant fragments	18.00
27. Sandstone, iron brown, medium-grained, with iron concretionary beds, massive	12.00
26. Sandstone, fine and medium-grained, thin bedded and shaly, with interbedded units of siltstone, contains plant fragments and mica flakes	5.00
25. Sandstone, white, mottled yellow-brown, medium-grained, with lenses of coarse pebbles, soft, massive, cross-bedded, contains thin beds of gray shale	27.00
24. Shale, yellow-green, clay	2.00
23. Sandstone, white to yellow-brown, fine-grained, interbedded with units of coarse gray sandstone, relatively soft, partially covered	95.00
22. Shale, gray-white, silty, hard, well bedded, interbedded with fine-grained sandstone, contains plant fragments and mica flakes	2.00
21. Sandstone, white to yellow-brown, very massive, coarse to fine grained, with lenses of pebbles, contains iron concretions, forms high prominent scarp	125.00
20. Siltstone, gray-brown, massive, soft	6.00
19. Shale, yellow-gray, clay	2.00
18. Sandstone, white to yellow-brown, medium to coarse grained, cross-bedded, contains abundant pieces of fossil wood and plant fragments	8.00
17. Shale, gray, silty, hard	2.00
16. Sandstone, white to yellow-brown, coarse, with pebble lenses, massive, cross-bedded, poorly sorted, has interbedded zones of very fine-grained sandstone, contains fragments of fossil wood	5.00
15. Shale, yellow-green	2.00
14. Shale, red	2.00
13. Shale, yellow-green, clay	2.00
12. Sandstone, yellow-brown, very fine-grained, thin-bedded and laminated, contains mica flakes	3.00
11. Sandstone, white, medium to coarse grained, cross-bedded, massive and soft	5.00
10. Sandstone, gray-brown, fine-grained, thin-bedded and laminated, with interbedded units of gray shale	2.00

9.	Sandstone, white, mottled yellow, medium grained, with lenses of coarse pebbles, weathers gray on surface, unit relatively soft	12.00
8.	Shale, green	6.00
7.	Sandstone, very fine-grained, thin-bedded and laminated, contains lenses of coarse pebbles, with interbedded units of green shale	5.00
6.	Shale, red, mottled gray	4.00
5.	Sandstone, gray-white, very fine grained, weathers yellow-brown at surface, lower four meters thin-bedded and laminated with mica flakes, upper part massively bedded, white, with pebbles up to 1 cm. in diameter, some thin zones impregnated with a dry, black, bituminous material, unit in general soft, forming low platform	75.00
4.	Sandstone, gray-white, coarse, massive, cross-bedded	8.00
3.	Sandstone, gray-white, fine-grained, thin-bedded and laminated, interbedded with gray-blue shale, contains mica flakes and plant fragments	5.00
2.	Sandstone, white and yellow-brown, massive, cross-bedded, coarse, with iron concretions and lenses of quartz pebbles, partially covered	39.00
1.	Sandstone, yellow-brown, massive, cross-bedded, contact zone covered, cannot tell for sure relationship	20.00
	Total	589.00

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THE ABSORPTION OF INFRARED RADIATION BY CLAY MINERALS

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ABSTRACT. Infrared absorption spectrograms by pulverized minerals of the kaolin, montmorillonite, and illite groups in the 2 to 15 micron wave length bands are shown. The kaolin minerals have a distinctive absorption but those from the other groups are less clearly defined. Spectrograms of gibbsite, brucite, quartz, opal, and muscovite are shown because of their structural relationships to the clay minerals.

INTRODUCTION

VARIOUS techniques, such as optical, chemical, thermal, and structural methods, have been used to determine and differentiate clay minerals. Another tool, infrared absorption by the pulverized clay minerals has been proposed (Keller, 1948). Although this technique is still in the exploratory stages enough information has been accumulated from numerous empirical measurements on clay minerals to present some typical patterns characteristic of them. The preliminary report will also supply information about which inquiries have been received. It should be realized that only a beginning in the work has been made, and only qualitative results have been obtained. Instrumentation needs to be improved, and after more measurements are made on various different mineral groups probably some definite assignment of absorption peaks to specific atomic groups will be possible. Quantitative methods are still before us.

The absorption of infrared radiation has been utilized as a powerful determinative and analytical tool by chemists, especially in work on organic compounds. So characteristic are the absorption bands within the 2-15 micron wave length spectrum of certain chemicals that they may be "finger printed" by their absorption spectrograms. The possible application of the technique to mineral determination has not been tested, particularly not for pulverized minerals like clays, and therefore the measurements reported herein constitute in part a trial of the applicability of the method to pulverized minerals as well

as a report on the properties of clay mineral specimens. Some preliminary work on the absorption of infrared by pulverized silica minerals has been reported (Keller and Pickett, 1949).

The principle involved in the selective absorption of infrared radiation depends upon the fact that the atoms of molecules are continuously in vibration at frequencies which fall within those of the infrared range (10^{12} to 10^{14} cycles per second) and that incident infrared radiation may be absorbed wholly or in part through interaction with the vibrating atoms. Moreover, in the infrared range there are absorptions correlating with the slower rotations of the molecules or the massive lattice vibrations of crystals. Although discrete "molecules" seldom exist in the crystal structure of most minerals, insofar as characteristic absorptions may be found, even empirically, for minerals, the basis for the results is sound.

The absorption frequency of simple or highly symmetrical molecules may be calculated approximately by the equation:

$$\nu = \frac{1}{2\pi c}\sqrt{\frac{k}{u}}$$

Where ν is the frequency in cm.$^{-1}$, c is the velocity of light, u is the reduced mass of the vibrating atoms, and k is the force constant which exists between the atoms. The formula has been simplified by reduction of constants, etc., in the concise and lucid introductory treatment of the subject by Barnes, Gore, Liddel and Williams, in their "Infrared Spectroscopy", but nevertheless, many chemical compounds, and certainly most minerals do not represent simple molecules, and it therefore lies beyond our present ability to calculate *a priori* their absorption characteristics. To this point, Barnes *et al.*, write:

"Although the mathematical approach has been of great value when applied to simple or highly symmetrical molecules, most of the information derived from infrared spectra is obtained by the application of the empirical method. This method consists of comparing the spectra of the largest obtainable number of different molecules having a common atomic group. By a process of elimination, it is often possible to find an absorption band whose frequency remains constant throughout the series. The presence, in an unknown, of an absorption at this frequency may reasonably form the basis for a guess

that the particular atomic group is present. Confidence in this method can be obtained only by successful applications in a large number of cases."

The apparatus used in these measurements is a Beckman Model IR-2 infrared spectrophotometer. Briefly, infrared radiation from a rich source is dispersed by a rock salt prism into a spectrum from which relatively narrow wave length bands are selected and transmitted along a path to a sensitive thermocouple. The intensity of the radiation transmitted is measured with the sample, and without it, in the absorption chamber, and the per cent transmission obtained thereby. High sensitivity of the instrument is achieved by suitable electronic amplification. The current infrared spectrometers embody highly advanced improvements over the apparatus which was available only a few years ago. Many of the older measurements of infrared absorption have been revised.

In this study, from 5 to 10 milligrams of the finely pulverized mineral was stirred and dispersed in 2 drops of Nujol (medicinal mineral oil) which filled the absorption chamber. The latter consists of rock salt plates which are separated by shims of variable and selected thicknesses, and held together by a metal frame. Nujol has been used as a suspending medium because it has a satisfactory viscosity, because its index of refraction lessens the scattering reflectance from the mineral particles, and because its own absorption spectrum is relatively simple. It should be recognized that the indices of refraction of both Nujol and a dispersed mineral may be radically different in the infrared range than they are in the visible spectrum. Regarding the absorption spectrogram of the suspending medium, it has been suggested that a single pure substance which could be purified chemically and reproduced closely might be preferred as a suspending medium to one like Nujol which is a complex mixture. Theoretically this is correct, but practically no pure liquid is known which has a simple absorption spectrum and also possesses the other properties which are desired for the infrared work. Because Nujol is a mixture, many tiny absorption peaks of individual constituents are averaged out, and the curve is flat enough that absorptions occurring within the susupended mineral show up.

About four hours are required to make a run and plot it.

After this manuscript had been prepared for publication it was shown by the laboratory of the Carter Oil Company* that improved spectrograms in the higher wave lengths can be obtained by grinding the particles to sizes less than the wave lengths of the radiation used. The writers obtain better resolution in the OH absorption band using Nujol, but confirm from a few runs that the resolution at higher wave lengths is superior as run by Carter Laboratory. Absorption peaks may also be made to appear sharper if the horizontal axis is shortened in relation to the vertical, but maximum detail is maintained with ample length of horizontal axis.

EXPERIMENTAL RESULTS

An absorption graph of Nujol alone in the specimen chamber is shown in figure 1. Along the base of the abscissa is plotted the wave length of the radiation in microns and along the top is the corresponding frequency in wave numbers or reciprocal centimeter. Transmission of radiation in per cent is plotted on the ordinate. Nujol is relatively transparent to most infrared radiation, transmitting from 80 to 90 per cent over most of the spectrum. Slight absorption occurs at approximately 2.3 and 2.4 microns, and almost complete absorption (opacity) for a band at about 3.43 microns in wave length. Lesser absorption occurs from 3.6 to 3.72 microns and pronounced absorption at 6.86 and 7.28 microns. Numerous slight absorptions extend over wave lengths to about 11.0 microns and another prominent peak occurs at 13.86 microns. This "background" of absorption is unavoidably present in every measurement where a mineral was immersed in Nujol. It may be "subtracted" from the mineral graph to obtain the absorption characteristics of the mineral. The telltale characteristics of a positive nature of an irradiated compound are its absorption "peaks" or depressions. High transmission bands may be characteristic of certain compounds, but they constitute evidence of a negative type.

It may be recalled here that chemists have found OH groups absorb at different wave lengths between 2.7 and 3.1 microns depending upon the degree of hydrogen bonding of these groups with each other or with other O atoms in the lattice.

* Personal communication from Parke Dickey, 1949.

Where OH groups are held independently, *i.e.*, monomeric, within a crystal lattice the absorption is at about 2.75 microns. Where two or more OH groups are sufficiently close together, the hydrogen of the OH groups may assume an oscillating position between two oxygen atoms with the formation of a resonating bond between both oxygen atoms simultaneously, the so-called hydrogen bond. The dimeric groups absorb at about 2.85 microns and polymeric groups at about 2.95 microns. Evidence from minerals indicates that the absorptions for the polymeric bonding may extend to perhaps 3.1 microns. Free water, H_2O, absorbs in the 6.0 to 6.1 micron range, in addition to the 2.7 to 2.9 micron band. Many other absorption bands have been correlated with chemical bonds (Barnes *et al.*, 1944; Randall *et al.*, 1949) but most of these are not applicable to minerals. If mineralogy from infrared data is developed it may require a considerable backlog of factual data before generalizations can be accurately made (as was the case with organic chemistry).

INFRARED SPECTROGRAMS OF CLAY MINERALS

The kaolin group. Infrared absorption spectrograms typical of kaolinite, dickite, halloysite and endellite are shown in figure 2. Nos. 14, 70, 71, and 72 are of kaolinite clays from Georgia, South Carolina, Nevada, and California respectively. The infrared absorption of kaolinite is characterized by "free" hydroxyl absorption at about 2.75 microns (commonly 2.72 microns) and a comparatively lesser amount of ill-defined hydrogen bonded hydroxyl up to 3.1 microns The band between 3.1 and 7.55 microns is relatively featureless, except that free water, H_2O, may or may not be shown at about 6.1 microns. Absorption begins at about 8.1 microns and increases regularly in intensity to about 8.95 microns. Another peak of slightly greater absorption occurs at about 9.15 microns. Still higher absorption peaks occur at about 9.54 and 9.95 microns, whereupon transmission increases up to 10.46 microns. Two more pronounced absorptions occur at about 10.75 and 11.0 microns. Transmission (transparency to the band) increases as the radiation lengthens to about 12.2 microns. At higher wave lengths, notable absorptions occur at about 12.7, 13.4, and 14.5 microns.

Spectrograms of numerous other kaolinite samples show high similarity to these illustrated. The absorptions are so consistent that confidence in recognition of a kaolin group from its infrared spectrogram is soon established. Pronounced free OH absorption correlates well with the kaolinite crystal structure as interpreted from X-ray diffraction data.

Miloschite, No. 71, for example, appears from infrared data to fall within the kaolin group, confirming prior evidence (Grim and Rowland, 1942; Kerr and Hamilton, 1949). The commercial Edwin #2 clay, spectrogram No. 72 from California likewise shows kaolinite infrared absorption.

Dickite shows the same general type of infrared absorption as does kaolinite, and cannot be differentiated from it with certainty at the present stage of our measurements. No. 65 shows very pronounced monomeric OH absorption at 2.72 microns which was lost upon calcination at 780°C. for 14 hours (see 65A). The characteristic absorption of the raw clay from 7.5 to 15 microns has also been obliterated or subdued after the 780° calcination, which likewise breaks down the crystal structure. Obviously the bonds between silica, alumina, and hydroxyl groups are responsible for the several absorptions shown by the raw clay but their specific assignment is not now known.

Dickite No. 69 shows less intense OH bonding than did No. 65. Various intermediate intensities of absorption in the 2.75 band have been observed on other dickites.

Endellite, No. 8, is characterized by pronounced absorption at 2.8 microns, due to free OH groups, and at 3.0 and 3.2 microns, due to hydrogen-bonded hydroxyl. At higher wave lengths the absorption of endellite parallels that of kaolinite but it is more subdued. The endellite sample was prepared by grinding under water endellite clay still wet with quarry moisture, drying sufficiently at room temperature and irradiating immediately. Another sample of powder which was "dried" in an atmosphere of 80 per cent relative humidity for two weeks gave the same absorption curve as the one shown. Molecules of interlayer water sheets in endellite, as postulated by Hendricks, are linked by polymeric bonds, and are linked to O of silica tetrahedra by hydrogen bonds of a slightly different type. Infrared absorption is in accord.

Halloysite, No. 73, shows strong OH absorption at 2.74

microns but notably less in the higher hydroxyl bands. This is in keeping with its lower water content than endellite.

As has been stated previously, we lack information on the correlation between the absorption peaks and the chemical bonds responsible for them. However, it may be suggested that the peaks occurring at 12.7 and 14.5 microns in kaolinite may arise from silica tetrahedra, or a variety of silica structure, because pulverized quartz shows infrared absorption peaks at 12.6 and 14.5 microns (Keller and Pickett, 1949). Other assignments may be speculated but do not justify printing.

The montmorillonite group. Infrared spectrograms of montmorillonite group minerals are shown in figure 3. A Ca montmorillonite, No. 43, exhibits free OH at 2.72 microns, and well-defined hydrogen bond peaks at 2.91 and 3.1 microns. Strong absorption occurs between 8.0 and 10.3 microns, above which more radiation is transmitted. Smaller absorption peaks occur at 11.0, 11.8, and 13 microns.

Na montmorillonite, No. 45, shows less well-defined hydrogen-bonded OH than does its Ca analogue. Other specimens of Na and Ca montmorillonite similarly indicate that the absorptions of the latter are more sharply defined than those of Na montmorillonite. A possible reason for this may be that the interlayer water in the Na, swelling type, of montmorillonite has greater mobility of movement than in the more tightly bonded Ca montmorillonite. At wave lengths above 7.5 microns the absorptions of the two clays are usually similar.

Beidellite, No. 9, from Creede, Colorado, and No. 12, a H beidellite from Missouri Putnam soil colloid, show spectrograms like Ca montmorillonite plus a small, but recognizable absorption peak at 10.3 microns. Insufficient samples of beidellite have been run to know if the 10.3 micron absorption is diagnostic from other montmorillonites.

Nontronite, No. 8, shows a typical montmorillonite spectrogram. We have insufficient infrared data to differentiate between the members of the montmorillonite group.

The illite group. Figure 4. Illite from Illinois gave spectrogram No. 7. The OH and hydrogen-bonded hydroxyl are prominent in the 2.75-3.2 band, similar to that in montmor-

illonite. Probably the similarity between the two mineral groups in the hydrogen-bonded OH is due to interlayer water rather than their similar 2:1 layer structure. Illite differs from montmorillonite by absorbing relatively more intensely at 12.0, 12.6, about 12.8, and 14.5 microns. Kaolinite showed peaks at 12.7 and 14.5 microns, and quartz absorbs at 12.6, 12.9, and 14.5 microns. These absorptions at similar wave lengths are probably significant but the full meaning of them is not presently clear.

Spectrogram No. 42 is of the "Sarospatak clay" from Sarospatak, Hungary, which may be a mixed layer, illite-montmorillonite clay. The OH absorption might be assigned to either of the groups. The remainder of the spectrogram is disappointingly featureless. Such an absorption is logical however, if the distribution between the two clays is such that the low intensities of absorption of each are "diluted" and subdued by the cushioning effect of the other clay. Higher resolution and higher intensity of absorption is needed; improvement or modification in apparatus is necessary.

Attapulgite. A spectrogram of the amphibole-like attapulgite, is shown in No. 16. The absorption of OH and water at 2.75-3.1 and 6.0 microns is intense. Further absorptions occur at 8.2, 8.7-8.9, 9.75, 10.2, 11.0, 11.7, 12.6, 12.95, and 14.5 microns. Some of the absorptions of attapulgite are common to montmorillonite and some to kaolinite. Only a few specimens of attapulgite have been measured and therefore insufficient empirical data are available to make a very positive statement about the constancy of the above absorptions.

Clay lattice components. Because modified sheets of silica tetrahedra, gibbsite, and brucite are present in the clay minerals, their infrared absorption spectrograms are shown in figure 5. Gibbsite, No. 22, shows both free and hydrogen bonded hydroxyl in considerable quantity. Strong absorption occurs above 8.0 microns in wave length. Brucite, No. 21, shows primarily free OH groups. This difference in structure confirms the evidence from crystal structure by X-rays as described by Bragg (1937):

"The difference" (in brucite-gibbsite structures) "lies in the way in which the layers are packed on each other. In

brucite, the OH sheets of neighboring layers fit into each other in a close-packed way, one OH touching three OH in the next layer. In Al $(OH)_3$ each OH of one layer is *opposite* (italics by Bragg) an OH of the next layer, as if there were a strong specific attraction of one OH for the other . . . . Brucite and hydrargillite illustrate a progressive change in the nature of the OH group which has been summarized as follows by Megaw. At one extreme when the polarizing influence of the cation is small we have $(OH)'$ groups which act much like F′ ions. They pack together as if neutral towards each other, and the distance between O centres is large (3.22 Å for Mg $(OH)_2$). At the other extreme when the polarizing influence of the cation is large, there appears to be a powerful attraction between (OH) groups which draws them close together" (2.79 Å for Al $(OH)_2$). Hence the infrared absorption accords with crystal structural evidence.

Brucite absorbs strongly and with little evident characteristic fine structure above 8.0 microns.

Quartz is shown in spectrogram No. 66. No OH absorption is present. Some of the absorptions above 9.0 microns may be represented in the clay mineral absorptions, especially in kaolinite and illite. As more empirical data are assembled tentative computations of vibrational frequencies appear more logical and less conjectural. Evidence must be obtained, however, from different silica, alumina, and water linkages in various minerals. This is time-consuming and progress has not gone far.

Hyalite opal, No. 40, shows the water (2.7-3.0 microns) associated with silica. However, the clearly evident quartz absorptions, above 9.0 microns, presumably due to organized tetrahedral linkage, are not present in amorphous opal. A sheet of muscovite, shows strong monomeric, free OH, in No. 80 N. Its absorptions above 8.0 microns are correlateable in part with those of the 3-layer clays, and are encouraging despite present inadequacies.

We are optimistic that infrared absorption measurements contain considerably more structural information about minerals than we are able to interpret now. The technique appears to merit more investigation.

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Fig. 3. Infrared spectrograms of the montmorillonite group of clay minerals.
No. 43. Ca montmorillonite, Arizona. From R. E. Grim.
No. 45. Na montmorillonite, Wyoming. From R. E. Grim.
No. 9. Beidellite, Creede, Colorado. From U. S. National Museum.
No. 12. Beidellite, Putnam soil colloid, Soils Dept. Univ. of Missouri.
No. 8. Nontronite, near Troy, Idaho. Col. with V. E. Scheid.

Fig. 4. Infrared spectrograms of illite and attapulgite.
No. 7. Illite from Illinois.
No. 42. Clay from Sarospatak, Hungary. From R. E. Grim.
No. 16. Attapulgite, Attapulgus, Georgia. From Paul F. Kerr, Columbia University Collection.

Fig. 5. Infrared spectrograms of minerals related structurally to clays.
No. 22. Gibbsite, New Caledonia. Univ. of Missouri mineral collection.
No. 21. Brucite, Wakefield, Quebec. Univ. of Missouri mineral collection.
No. 66. Quartz, Graniteville, Missouri.
No. 40. Hyalite opal, Guanajato, Mexico. Univ. of Missouri mineral collection.
No. 30N. Muscovite, Jackson, No. Carolina. Univ. of Missouri mineral collection.

ECOLOGY OF MARSH AND BAY FORAMINIFERA, BARNSTABLE, MASS.

FRED B. PHLEGER AND WILLIAM R. WALTON

ABSTRACT. Fifty-five bottom samples were collected along three traverses in Barnstable Harbor, Massachusetts, and adjacent Cape Cod Bay. The Foraminifera populations are analyzed quantitatively and distribution patterns are described.

There are two principal Foraminifera facies in Barnstable Harbor and in adjacent Cape Cod Bay. Three subfacies are present in the harbor area and two subfacies occur in the Bay. Environmental conditions are described and are correlated with facies and subfacies distribution.

INTRODUCTION

THE purpose of this study is to examine Foraminifera faunas from Barnstable Harbor, Mass., and adjacent Cape Cod Bay, and to correlate the distribution with the known environmental factors.

The Barnstable Harbor area was chosen because of the great variation in environmental conditions. The harbor is small but contains all the environments characteristic of brackish water marshes (Johnson, 1925, pp. 522-528), and is adjacent to the open water of Cape Cod Bay where contrasting studies of the faunas can be made. Sandy Neck is a long sand spit between the marsh and bay environments and is the type of deposit which may be of some importance in older sedimentary rocks. It is believed that knowledge of potential micro-fossils adjacent to such a sediment may serve as a tool to point to the probable existence of a lenticular shoreline deposit in older rocks. Much work has been done on the environmental conditions existing in Barnstable Harbor by members of the Woods Hole Oceanographic Institution over a period of 2 years, and environmental conditions in this area are better known than for any other similar area along the Atlantic Coast.

No previous data are recorded on the Foraminifera of Cape Cod Bay. It is believed that the results of this study give an accurate general picture of the Foraminifera facies distribution in this part of the bay area. It is not possible to say that similar faunal facies occur elsewhere, but it is reasonable to postulate that sharp variations in the Foraminifera fauna

can be expected where similar conditions exist. It is hoped that other studies can be made in the future in order to extend knowledge of the ecology of tidal marshes and adjacent deposits.

ACKNOWLEDGMENTS

The samples were collected with the facilities of the Woods Hole Oceanographic Institution. Frances L. Parker assisted in identification of the species. The laboratory work was financed by the Office of Naval Research, under Contract N6onr-277, Task Order III. Information on ecology of the Barnstable Harbor area was furnished by J. C. Ayers of the Woods Hole Oceanographic Institution.

LOCATIONS OF SAMPLES

The area is located on the south side of Cape Cod Bay and includes approximately 100 sq. mi. Barnstable Harbor is largely a salt water marsh area separated from the open water of Cape Cod Bay by a sand spit (Sandy Neck) approximately 6 mi. long and ½ mi. wide. The harbor is connected with the bay by a tidal channel about 400 yds. wide at low water, extending the length of the harbor and varying in depth from .3 m. to 8 m.

The samples were collected during the summer of 1948 by F. B. Phleger, J. C. Ayers, and H. J. Turner. The bay samples are spaced 1 mi. apart in three traverses along the meridians 70°16′ W. Long., 70°12.7′ W. Long., and 70°21.3′ W. Long., and each traverse extends offshore for approximately 10 mi. In the harbor area the stations were spaced so that all the major environments were sampled and are in traverses which are approximate continuations of the bay traverses (fig. 1). The stations along the three traverses were spaced to obtain a representative fauna from all environments from the mainland side of the harbor, across the sand spit and into Cape Cod Bay. Traverse 3 is in the main channel of the harbor between Scorton Creek and Beach Point and continues into the bay. Locations of the stations are listed in table 1.

METHOD OF STUDY

Most of the Cape Cod Bay samples were collected with the bottom sampler constructed by Phleger. This gear obtains

a relatively undisturbed sample of the surface sediment and a short cross section extending an average of about 30 cm. beneath the surface. The upper 2 cm. of sediment from these samples was used for study of the Foraminifera. The sampler can be used only in sediment containing sufficient mud so that there is some cohesion between the particles. In sandy areas a small orange-peel dredge was used, which is modified to prevent washing of the sediments enroute to the surface of the water. Material for study was selected from the surface of each of these samples and was approximately the same amount of sediment as that selected from the short cores. Most of the samples at the very shallow stations within the harbor area were collected with a spatula.

It was considered undesirable to examine the entire sample from many stations due to the large amount of sediment in the sand samples, and only a small fraction of these was studied. Division of such samples was accomplished by means of a simple splitting device designed by Parker (1948, pp. 218-219). This apparatus consists of a small tray divided into two sections by a knife edge in the middle of a v-shaped trough inclined at approximately 45°. With this apparatus it is possible to make numerous divisions of the washed sediment and obtain a representative fraction of the entire sample. In samples where few specimens were found on first examination, the entire sample was treated with carbon tetrachloride and the residues were examined for forms not freed by flotation.

Methods used in the analysis of the data are those used by Phleger (1942) and Parker (1948). Percentages of all the species in each population were calculated. These are plotted by traverses to study variations that occur along the length of the traverses (tables 2-4). In addition, the harbor fauna percentages are plotted by ecologic zones because of the variety of existing environmental conditions (table 5).

Total population counts appearing in tables 2-5 are close approximations and are given as whole numbers. Distribution of the Foraminifera has been analyzed by plotting the faunas in two groups, the harbor fauna and the bay fauna. Each sample was classified according to general type of sediment and a brief description of the sediments is given in table 1.

THE FORAMINIFERA

THE SPECIES

Twenty-six species of Foraminifera have been identified. Some of the species are discussed briefly below and typical specimens are illustrated on plates 1 and 2. Only those species previously recorded from the North Atlantic are included in the following discussion.

Ammobaculites sp. has been assigned tentatively to the genus *Ammobaculites*. The majority of specimens lack the uniserial portion and further study is needed to reveal the internal structure of the species.

Ammobaculites cassis (Parker) varies from small and presumably young specimens to the large microspheric and megalospheric forms (plate 1). All variations occur together at most places. This species is found north from Cape Cod along the New England coast to Greenland. It is a typical sub-Arctic species and Cape Cod Bay appears to be the southernmost locality from which it has been recorded.

Armorella sphaerica Heron-Allen and Earland, a very small form which was described from the Antarctic, has been recorded from Keil Bay, Germany, and off Nonamesset Island, Mass. (Cushman, 1944). The latter is the only previously recorded occurrence from the Western Atlantic.

Eggerella advena (Cushman) is a common species in the New England region and occurs in great abundance in the Cape Cod Bay samples. It is typically a sub-Arctic species and has been found to occur abundantly in the North Atlantic.

Elphidium cf. *articulatum* (d'Orbigny) occurs only in the bay samples from water depths greater than 26 m. and is present in low percentages. It has been recorded previously only from Casco Bay, Maine (Cushman, 1944).

Elphidium incertum (Williamson) is present in both the bay and the harbor faunas but is much more abundant in the bay. It shows many variations from opaque white, thick-walled specimens to clear, almost transparent tests and has a great range in size. This species is very common along the New England coast.

Eponides frigidus (Cushman) var. *calidus* Cushman and Cole occurs in most of the bay samples. It is one of the com-

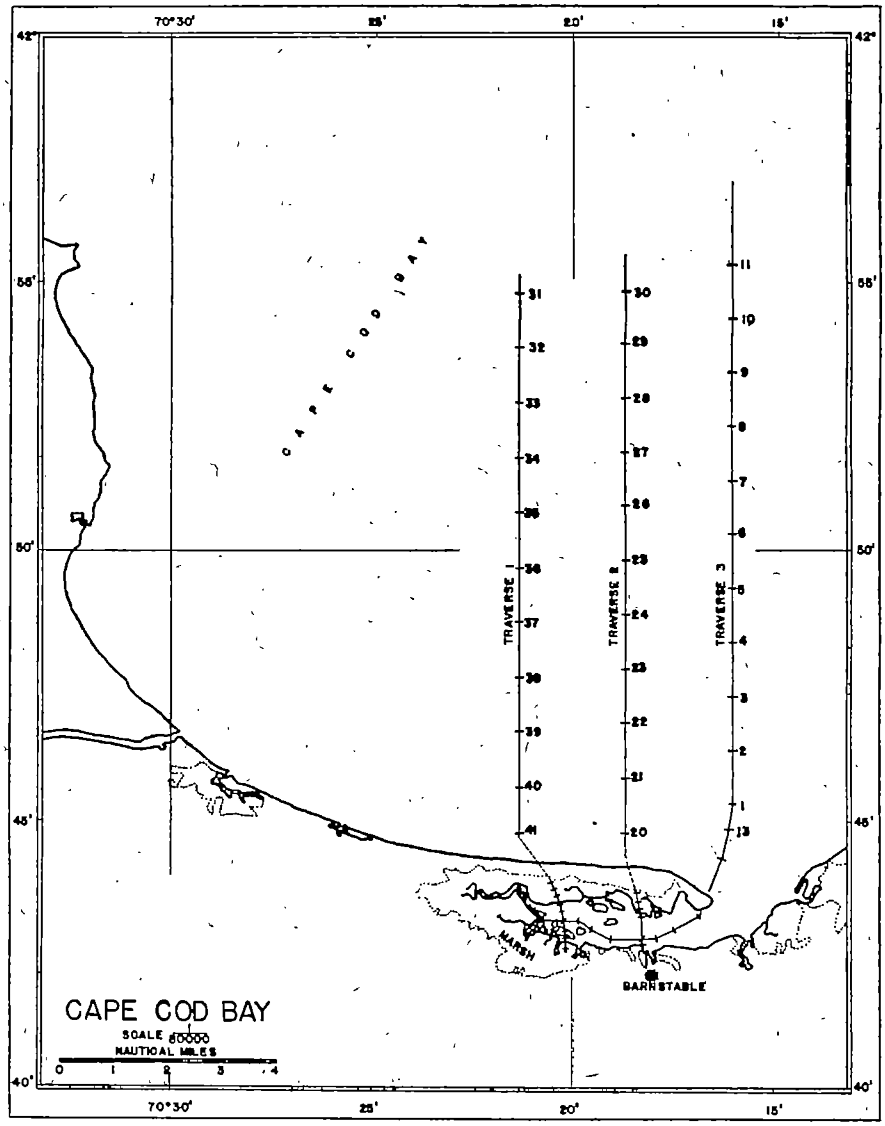


Figure 1
Chart of a portion of Cape Cod Bay showing location of traverses.

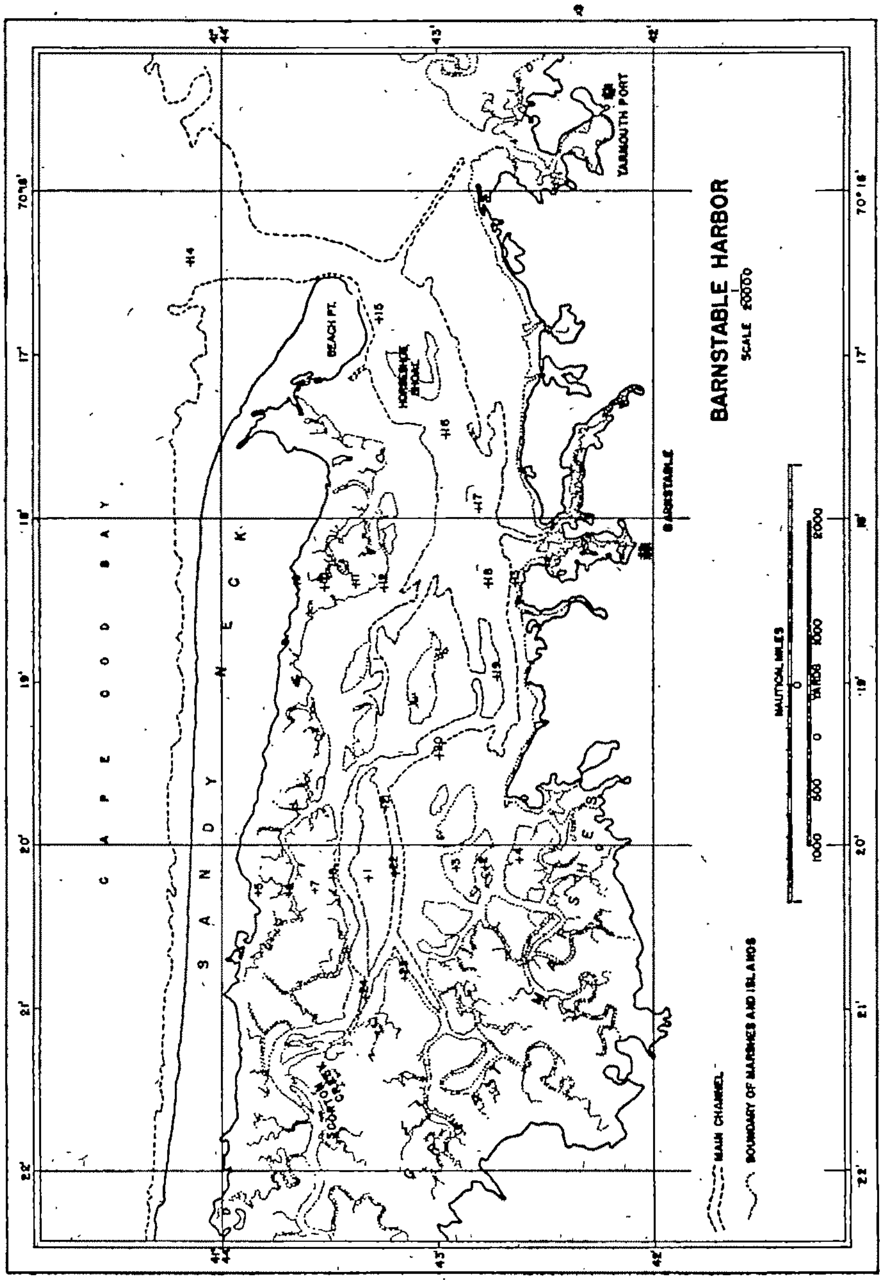


Figure 2
Barnstable Harbor chart showing locations of stations.

monest of the shallow-water forms from the New England coastal region (Cushman, 1944).

Proteonina atlantica Cushman is present in great abundance in the bay samples from the shallowest sample at 19 m. to the deepest at 38 m., 10 miles offshore. It is cool temperate to Arctic in distribution, being very common around Greenland and along the New England Coast.

Miliammina fusca (H. B. Brady) occurs almost entirely in the harbor area, but a few specimens were found in the Bay. It has been reported previously from Casco Bay, Maine (Cushman, 1944).

Reophax curtus Cushman is scattered in the bay fauna, being present in low frequency at many stations. It has been recorded previously in the vicinity of Vineyard Sound (Cushman, 1944).

Reophax cf. *arctica* H. B. Brady has been found in a few bay samples occurring with *R. curtus* and *R. scottii*.

Reophax scottii Chaster occurs with *R. curtus* and is fairly abundant in many of the bay samples. It has been reported at only one other locality in the Western Atlantic, off Gay Head, Mass. (Cushman, 1944).

Trochammina inflata (Montagu) is present in the harbor fauna in great abundance. Specimens vary in size, but most are large and well developed. This species is common along the New England coast.

Explanation of Plate 1

Figure

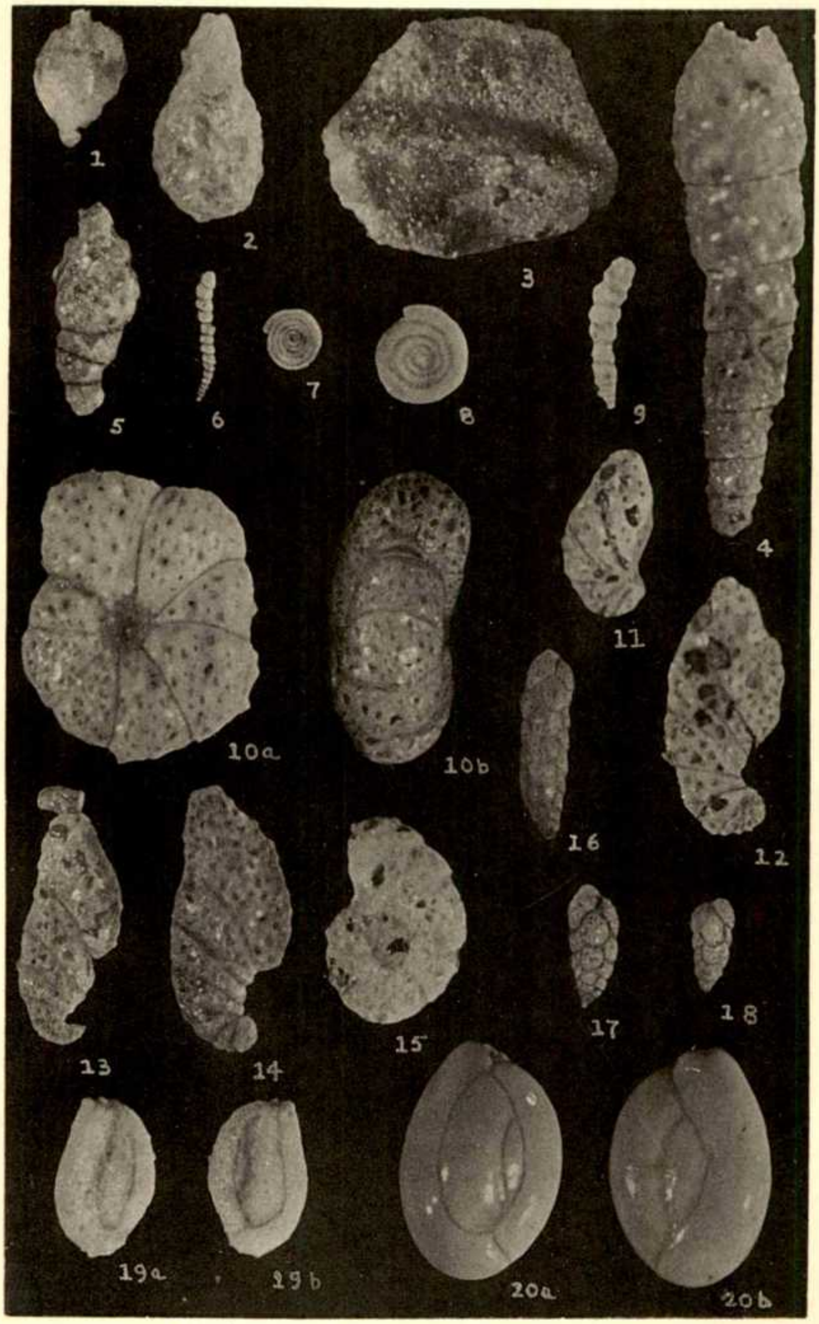
1. *Armorella sphaerica* Heron-Allen and Earland. x44. Sta. H5.
2. *Proteonina atlantica* Cushman. x42. Sta. B9.
3. *Webbinella* (?) sp. x44. Sta. H5.
4. *Reophax* sp. x40. Sta. B11.
5. *Reophax curtus* Cushman. x27½. Sta. B6.
6. *Reophax scottii* Chaster. x40. Sta. B6.
7. *Ammodiscus* sp. x39. Sta. B3.
8. *Ammodiscus* sp. x42. Sta. B2.
9. *Reophax* cf. *arctica* H. B. Brady. x43. Sta. B10.
10. *Labrospira crassimargo* (Norman). x39. a) side view; b) apertural view. Sta. B9.

11-14. *Ammobaculites cassis* (Parker). 11-12) x40; 13-14) x26½. 11) Sta. B33; 12-14) Sta. B22.

15. *Ammobaculites* sp. x42. Sta. H24.

16-18. *Eggerella advena* (Cushman). 16-17) x40; 18) x44. Sta. B9.

19. *Milammina fusca* (H. B. Brady). x42. Sta. H6.
20. *Quinqueloculina seminula* (Linne). x41. Sta. B2.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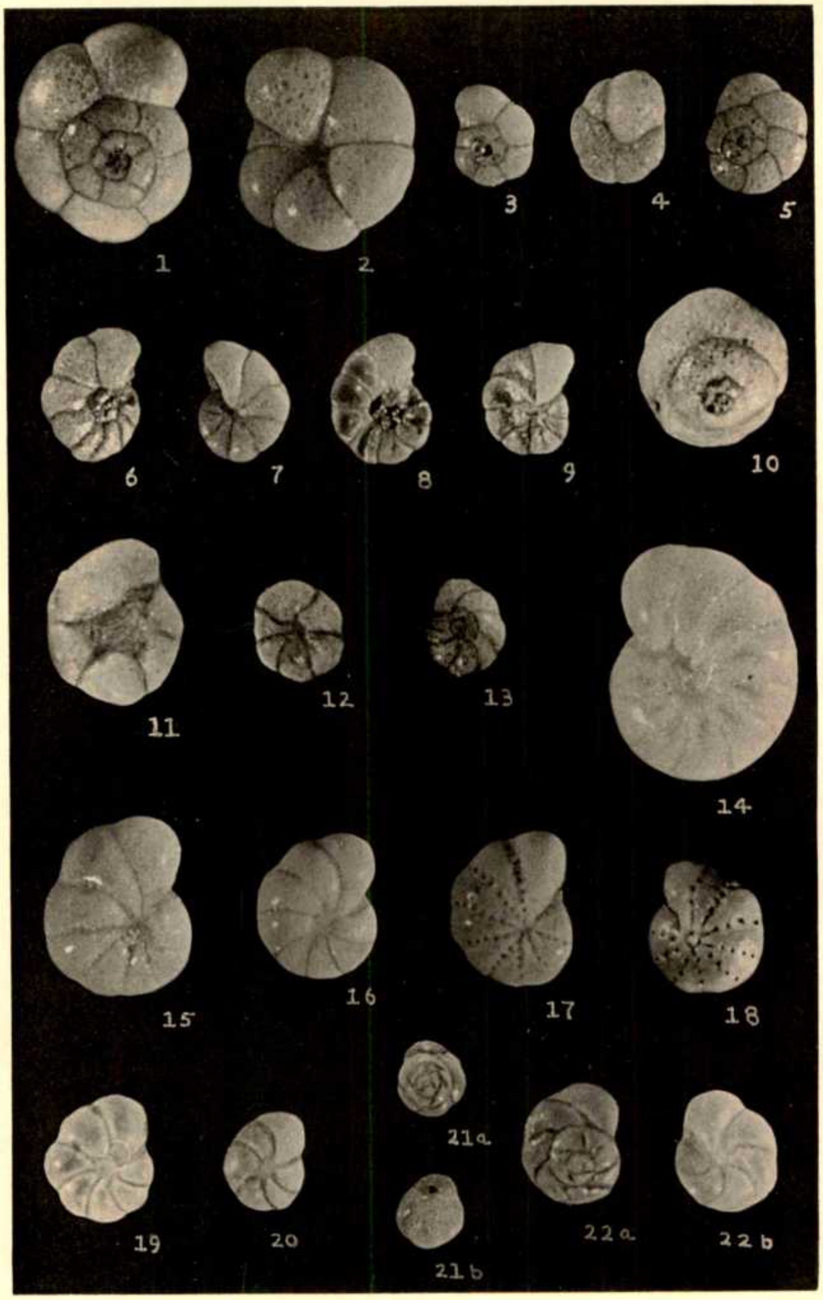
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Trochammina lobata Cushman occurs generally throughout the harbor and the bay faunas. It is common along the New England coast and has been reported at numerous stations by Cushman (1944) and Parker (1948).

Trochammina rotaliformis J. Wright occurs with low frequency in both harbor and bay samples. It has been reported as common in Hudson Bay and at other stations along the New England coast (Cushman, 1948).

Trochammina macrescens H. B. Brady occurs in the harbor samples in about the same proportion as *T. inflata*. All variations of the chambers occur in these forms from complete deflation to the normal form. The only other recorded Atlantic occurrences are those from brackish water around the British Isles.

Trochammina squamata Parker and Jones and allied species (Höglund, 1947) have not been separated. They occur together at the same stations and are included in one count. This group occurs at most harbor and bay stations.

HARBOR FACIES

Occurrence of Foraminifera in the Barnstable Harbor samples is listed in tables 2-5. The most abundant species is *Trochammina inflata* which comprises 10 per cent to 100 per

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Explanation of Plate 2

Figure

1-3. *Trochammina inflata* (Montagu). x43. 1-2) Sta. H6; 3) Sta. H1.

4-5. *Trochammina lobata* Cushman. x41. Sta. B3.

6-9. *Trochammina macrescens* H. B. Brady. x40. 6-7) Sta. H6; 8-9) Sta. H4.

10-11. *Trochammina rotaliformis* J. Wright. x40. Sta. H6.

12-13. *Trochammina squamata* Parker and Jones. 12) x39.; 13) x42. Sta. B9.

14-16. *Elphidium* cf. *articulatum* (d'Orbigny). 14) x43., Sta. B6; 15) x41. Sta. B6; 16) x39., Sta. B4.

17-18. *Elphidium incertum* (Williamson). 17) x41.; 18) x44. Sta. B9.

19-20. *Elphidium subarcticum* Cushman. 19) x43.; 20) x42. 19) Sta. H1; 20) Sta. H6.

21. *Eponides frigidus* (Cushman) var. *calidus* Cushman and Cole. x41. a) ventral view; b) dorsal view. Sta. B9.

22. *Valvulineria* sp. x39. a) ventral view; b) dorsal view. Sta. H6.

TABLE 1

Location of Stations

Sta.	N. Lat.	W. Long.	Depth in Meters	Sediment Description
B1	41°45.3′	70°16′	14 m.	Medium sand
B2	41°46.2′	70°16′	19 m.	Medium sand
B3	41°47.3′	70°16′	23 m.	Fine sand
B4	41°48.3′	70°16′	23 m.	Mud and sand
B5	41°49.3′	70°16′	25 m.	Mud and sand
B6	41°50.3′	70°16′	31 m.	Mud and sand
B7	41°51.3′	70°16′	32 m.	Mud and sand
B8	41°52.3′	70°16′	33 m.	Mud
B9	41°53.3′	70°16′	34 m.	Mud
B10	41°54.3′	70°16′	36 m.	Mud
B11	41°55.3′	70°16′	38 m.	Mud
B13	41°44.8′	70°16.1′	4 m.	Clean coarse sand and pebbles
B20	41°44.8′	70°18.7′	8 m.	Clean fine sand
B21	41°45.7′	70°18.7′	15 m.	Fine sand and silt
B22	41°46.8′	70°18.7′	21 m.	Fine sand and silt
B23	41°47.7′	70°18.7′	21 m.	Fine sand and silt
B24	41°48.7′	70°18.7′	26 m.	Mud and sand
B25	41°49.7′	70°18.7′	28 m.	Mud and sand
B26	41°50.7′	70°18.7′	28 m.	Mud and sand
B27	41°51.7′	70°18.7′	31 m.	Mud
B28	41°52.7′	70°18.7′	32 m.	Mud and sand
B29	41°53.7′	70°18.7′	34 m.	Mud
B30	41°54.7′	70°18.7′	38 m.	Mud
B31	41°54.7′	70°21.3′	38 m.	Mud
B32	41°53.7′	70°21.3′	36 m.	Mud
B33	41°52.7′	70°21.3′	34 m.	Mud
B34	41°51.7′	70°21.3′	32 m.	Mud
B35	41°50.7′	70°21.3′	30 m.	Fine silt and mud
B36	41°49.7′	70°21.3′	30 m.	Fine silt and mud
B37	41°48.7′	70°21.3′	28 m.	Fine silt and mud
B38	41°47.7′	70°21.3′	26 m.	Fine silt and mud
B39	41°46.7′	70°21.3′	22 m.	Fine silt and mud
B40	41°45.7′	70°21.3′	20 m.	Fine silt and mud
B41	41°44.7′	70°21.3′	12 m.	Clean fine sand
H1	41°48.4′	70°20.1′	Inter-tidal	Clean fine sand and shell fragments
H2	41°42.8′	70°20′	"	Coarse silt
H3	41°42.7′	70°20.1′	"	Silt
H4	41°42.5′	70°19.9′	"	Silt, high organic content
H5	41°43.9′	70°20.3′	"	Silt, high organic content
H6	41°43.7′	70°20.2′	"	Silt, high organic content
H7	41°43.6′	70°20.1′	"	Silt, high organic content
H8	41°43.5′	70°20.1′	"	Silty clay
H9	41°43.7′	70°18.4′	"	Silty clay, high organic content

TABLE 1 (Continued)

Sta.	N. Lat.	W. Long.	Depth in Meters	Sediment Description
H10	41°43.5′	70°18.4′	"	Silty clay, high organic content
H11	41°43.4′	70°18.4′	"	Silty clay, high organic content
H12	41°43.3′	70°18.4′	"	Medium clean sand
H13	41°42.6′	70°18.4′	"	Fine sand and coarse silt
H14	41°44.2′	70°16.5′	3 m.	Medium clean sand
H15	41°43.2′	70°16.8′	3 m.	Medium clean sand
H16	41°42.9′	70°17.5′	3 m.	Medium clean sand
H17	41°42.7′	70°17.9′	3 m.	Medium clean sand
H18	41°42.6′	70°18.4′	.6 m.	Medium clean sand
H19	41°42.6′	70°18.8′	.3 m.	Fine clean sand
H20	41°43.1′	70°19.5′	.3 m.	Fine clean sand
H21	41°43.3′	70°19.7′	.3 m.	Fine clean sand
H22	41°43.3′	70°20.2′	.3 m.	Coarse silt and fine sand
H23	41°43.4′	70°21′	.3 m.	Clean fine sand
H24	41°43.4′	70°21′	.3 m.	Clean fine sand

cent of the fauna in each harbor sample, except those which were taken from the channel. Next in abundance is *T. macrescens* which also is a large percentage of the fauna. *T. rotaliformis* is not abundant and occurs both in the harbor and bay faunas (see tables 2-4). *Armorella sphaerica* and *Webbinella* (?) sp. are all restricted to the harbor but make up a very small per cent of the samples in which they occur. *Ammobaculites* sp. occurs only in the harbor and although restricted in distribution is a significant percentage of the fauna in the samples where it occurs (see H8, H22, H21, tables 2, 4).

Trochammina lobata and *Trochammina squamata* and varieties occur in fairly high percentages throughout both the harbor and bay faunas (table 2). *Elphidium incertum* and *Elphidium subarcticum* both are present in the harbor but are much more abundant in the bay (table 2).

There are four major zones in the harbor area based on floral distribution; the *Spartina patens* zone, in which those forms live that will endure wetting by tidal action for only a brief period, the *Spartina glabra* zone, in which those forms live that require daily submergence by the tides, the intertidal zone or "mud flat" zone, and the *Zostera* zone (eel grass zone), which is continually submerged (Johnson, 1925). In Barnstable Harbor parts of the *Zostera* zone are exposed at low tide.

The greatest total populations of harbor Foraminifera occur in the high marsh (*Spartina patens* and *Spartina glabra* zones). The fauna is composed principally of *Trochammina inflata* and *T. macrescens* from stations H8, H4, H5, H6, H7, H10, and H11. *Armorella sphaerica, Webbinella* (?) sp.

TRAVERSE I																				
STATION	H4	H2	H3	H22	H1	H8	H7	H6	H5	B41	B40	B39	B38	B37	B36	B35	B34	B33	B32	B31
DEPTH IN METERS										12	20	22	26	28	30	30	32	34	36	38
TOTAL BENTHONIC POPULATION	6700	100	1100	500	700	1700	9600	9300	6900	300	500	800	1400	1900	800	400	1400	1600	1500	300
BENTHONIC SPECIES IN %																				
AMMOBACULITES SP.			42	33	19															
A. CASSIS													4	10	8		2	3	2	2
ARMORELLA SPHAERICA							2	2												
AMMODISCUS SP.													1		2			2		
EGGERELLA ADVENA		67						.1			33	23	34	30	37	27	26	36	35	48
ELPHIDIUM ARTICULATUM													4		2					
E. INCERTUM								.3		75			4	7	3	27			2	10
E. INCERTUM VAR. CLAVATUM										13				3						
E. SUBARCTICUM					.7			.1				8	5	3		9	5			5
EPONIDES FRIGIDUS VAR. CALIDUS												4	2							
GLOMOSPIRA CF. GORDIALIS														.8						
LABROSPIRA CRASSIMARGO				3																
PROTEONINA ATLANTICA											47	58	34	33	43	36	61	64	49	24
MILIAMMINA FUSCA			6		.1		9	25	2				1							
REOPHAX CURTUS													4		2		2		2	
R. SCOTTII													4	6	4		2	1	6	7
TROCHAMMINA INFLATA	26	33	40	43	46	90	10	12	39			4		.8						
T. LOBATA			1	3	7	8	2	9	5	13	7	4	1	.8				1		
T. MACRESCENS	74		6	14	25	3	67	33	45											
T. CF. ROTALIFORMIS				3			1	4	3									1		
T. SQUAMATA			4		3						14		1					1	2	2
WEBBINELLA (?) SP.	.2						5	8	5											
VALVULINERIA SP.	.3						4	4												

TABLE 2

Percentage Distribution of Foraminifera in Traverse 1

and *Valvulineria* sp. are confined to these zones, and the greatest frequency of *Miliammina fusca* occurs in the high marsh (table 5). The total amount of organic material in the sediments also is much greater here. Apparently anomalous faunas occur at stations H2 and H9. Station H2 is located on a small sandy island in the *Spartina glabra* zone, but the total population is small and only two species are found. Sample H9,

TRAVERSE 2

STATION	H13	H18	H12	H11	H10	H9	B20	B21	B22	B23	B24	B25	B26	B27	B28	B29	B30
DEPTH IN METERS							8	15	20	21	26	28	28	31	32	34	38
TOTAL BENTHONIC POPULATION	32	8	23	6600	1100	4	4	2	900	1100	9600	1200	1500	1400	1500	1800	700
BENTHONIC SPECIES IN %																	
AMMOBACULITES CASSIS									7		4	1	6	9	2	3	2
AMMODISCUS SP.									3	3	.5						
ARMORELLA SPHAERICA					2												1
EGGERELLA ADVENA							75		14	18	8	54	32	26	25	32	37
ELPHIDIUM ARTICULATUM											1		4				3
E. INCERTUM	53		22								5	8	4	2	4	3	26
E. INCERTUM VAR. CLAVATUM											.5		2				3
E. SUBARCTICUM			26						3		.1				2	3	1
EPONIDES FRIGIDUS VAR. CALIDUS									3		.2		4		2	.9	1
GLOMOSPIRA CF. GORDIALIS										3			2		2		
LABROSPIRA CRASSIMARGO														1			1
PROTEONINA ATLANTICA									52	67	55	24	26	49	54	41	14
MILIAMMINA FUSCA	13		17	41							.3						
Q. SEMINULA											.3					.9	
REOPHAX CURTUS											2	4	4	1			
R. SCOTTII											.3	1	11	8	2	6	6
R. SCORPIURUS																4	
SPIROPLECTAMMINA BIFORMIS													2	2	2	.9	
TROCHAMMINA INFLATA	22		30	37	23	100											
T. LOBATA				2	7			100	14	9	22	3				.9	
T. MACRESCENS	13			20	30												
T. CF. ROTALIFORMIS				.5	30		25		3			1					
T. SQUAMATA		100	4								.5	3	2	1	4	6	5
WEBBINELLA (?) SP.					10												

TABLE 8

Percentage Distribution of Foraminifera in Traverse 2

taken at the junction of the marsh zone and the sand dunes of Sandy Neck, contains four specimens of *Trochammina inflata*.

Total populations are much smaller in the intertidal flat zone than in the high marsh at stations H1, H8, H12, and

TRAVERSE 3																					
STATION	H24	H23	H22	H21	H20	H19	H18	H17	H16	H15	H14	B13	B1	B2	B3	B4	B5	B6	B8	B9	B10
DEPTH IN METERS												4	14	19	23	23	25	31	32	34	36
TOTAL BENTHONIC POPULATION	43	73	500	100	—	—	8	18	54	1	2	12	2	200	700	2700	4900	4300	1900	2300	1300
BENTHONIC SPECIES IN %																					
AMMOBACULITES SP.	5	1	33	15																	
A. CASSIS															1		3	3	2	.7	6
AMMODISCUS SP.		1												.6	.2			2			
EGGERELLA ADVENA	7	1						17						11	54	50	47	29	25	55	54
ELPHIDIUM ARTICULATUM												8						6			
E. INCERTUM								11				17		33	7	7	1	7	3	12	6
E. INCERTUM VAR. CLAVATUM													100	.6		1				.4	5
E. SUBARCTICUM	7	1						11						2	.2			.9		2	.3
EPONIDES FRIGIDUS VAR. CALIDUS														.6				1			.6
GLOMOSPIRA CF. GORDIALIS														6				.9		.4	.6
LABROSPIRA CRASSIMARGO			3									8						.4		.4	
PROTEONINA ATLANTICA														.6	20	32	34	29	65	19	24
MILIAMMINA FUSCA	9	44													.2			.6			
Q. SEMINULA												8		9							
REOPHAX CURTUS															.2		.7	2	.8	.4	.6
R. SCOTTII															2		3	5	2	2	2
TROCHAMMINA INFLATA	61	43	43	72				11		100					.6		.7		.4		
T. LOBATA	7	6	3	15				6						6	11	9	9	9	.8	1	.3
T. MACRESCENS	2	3	14					6									.7				
T. CF. ROTALIFORMIS			3											4	.2		1		.4		
T. SQUAMATA	2						100	39	100		100	58		26	3	1		3	2	6	1

TABLE 4

Percentage Distribution of Foraminifera in Traverse 3

BARNSTABLE HARBOR STATIONS	ZOSTERA AND BELOW ZOSTERA ZONES											MUD FLAT ZONE				SPARTINA PATENS AND SPARTINA GLABRA ZONES								
STATION	14	15	16	17	18	19	20	21	22	23	24	1	8	12	13	2	3	4	5	6	7	9	10	11
TOTAL BENTHONIC POPULATION	2	1	54	18	8	—	—	100	500	100	50	700	1700	20	30	100	1100	6700	8900	9300	9600	4	1150	6700
BENTHONIC SPECIES IN %																								
AMMOBACULITES SP.								15	33	1	5	19					42							
AMMODISCUS SP.										1														
ARMORELLA SPHAERICA																				2	2		2	
EGGERELLA ADVENA				17						1	7					67				.1				
ELPHIDIUM INCERTUM				11										22	53					.3				
E. SUBARCTICUM				11						1	7	.7		26						.1				
LABROSPIRA CRASSIMARGO									3															
MILIAMMINA FUSCA										44	9	.1		17	13		6		2	25	9			41
TROCHAMMINA INFLATA		100		11				72	43	43	61	46	90	30	22	33	40	26	39	12	10	100	23	37
T. LOBATA				6				15	3	6	7	7	8				1		5	9	2		7	2
T. MACRESCENS				6					14	3	2	25	3		13		6	74	45	33	67		30	20
T. CF. ROTALIFORMIS									3										3	4	1		30	.5
T. SQUAMATA	100		100	39	100						2	3		4			4							
WEBBINELLA (?) SP.																		.2	5	8	5		10	
VALVULINERIA SP.																		.3		4	4			

TABLE 5

Percentage Distribution of Harbor Foraminifera arranged According to Ecologic Zones

H13. Stations H12 and H13 appear to contain the only characteristic intertidal flat fauna. The presence of *Elphidium incertum* makes this zone distinctive. Apparent faunal anomalies in this zone exist at stations H1 and H8. Stations H1 and H8 have relatively high total populations although located in the intertidal flat zone which generally is characterized by small populations.

The channel stations (*Zostera* zone or below *Zostera* zone), H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, and H24, are always submerged. The Foraminifera populations of the channels are small but generally contain the same species as the other zones, with the exception of stations H21, H22, H23, and H24 which have the greatest total populations of the channel stations, and correspond more closely to the fauna of the intertidal flat and high marsh areas in having numerous specimens of *Trochammina inflata* and *T. macrescens* (table 5).

BAY FACIES

The bay fauna is characterized by *Proteonina atlantica* and *Eggerella advena* which make up approximately 90 per cent of the Foraminifera populations. *Proteonina atlantica* is somewhat more abundant than *Eggerella advena*, but both species occur in most bay samples. *Ammobaculites cassis* is fairly abundant and is restricted to the bay. The following species are restricted to the bay but constitute a relatively small percentage of the samples in which they occur: *Ammodiscus* sp., *Elphidium articulatum*, *Eponides frigidus* var. *calidus*, *Glomospira* cf. *gordialis* and *Quinqueloculina seminula*. *Reophax* is restricted to the bay and the various species usually occur in the sand samples.

There are two subfacies in the bay fauna which are characterized by different species and different frequencies of species. The nearshore facies is developed on the sandy bottom which is present at depths shallower than approximately 20 m. It is characterized by *Eggerella advena* and *Proteonina atlantica* which compose most of the Foraminifera population although 3 or 4 other species may occur in low abundance in any sample.

A second bay subfacies is present from approximately 20 to 30 m. water depth to the outer end of the traverses; this is the area which has a mud and sand or mud bottom. The

following species appear to be restricted to the mud and sand or mud subfacies:

Ammodiscus sp.
Ammobaculites cassis
Elphidium articulatum
Eponides frigidus var. *calidus*
Glomospira cf. *gordialis*
Quinqueloculina seminula
Reophax scorpiurus
R. scottii
R. curtus

The following species generally have their highest frequencies in the mud and sand and mud subfacies:

Elphidium incertum
E. incertum var. *clavatum*
E. subarcticum
Trochammina squamata

Some faunal mixing is apparent in the samples from traverse 3, especially between the harbor facies and the sand subfacies of the bay. This probably is due to strong tidal currents localized near the entrance of the harbor.

DISCUSSION

Currents in Barnstable Harbor are controlled almost exclusively by the tides. There is very little fresh water drainage into the harbor. The physiography of the harbor is such that the tide is asymetrical, there being 7 hours of ebb and 5 hours of flood. Intertidal flats within the harbor are little affected by the strong currents of late ebb, for they become exposed before the time of maximum ebb currents. The small populations of Foraminifera from the channel stations undoubtedly are to be correlated with tidal scour.

The intertidal flats (stations H1, H8, H12, and H13) are not affected by the strong currents of late ebb but do shift with other stages of the tide and are practically barren of vegetation. Lack of protective vegetation and the coarseness of the shifting sand of the intertidal flats probably are not conducive to a large Foraminifera population (table 5).

The largest Foraminifera populations in the harbor area occur in the "high marsh" (*Spartina patens* and *Spartina*

glabra zones combined). There are two possible explanations for these large populations: either environmental conditions in the high marsh will support an abundant Foraminifera fauna, or specimens are washed there by the tidal currents. The high marsh areas are covered by a matted growth of marsh grasses and are completely submerged by only the highest spring tides or by occasional wind-driven tides. These areas usually are wetted from underneath twice daily at high tide. There is a high production of a variety of organisms and organic material accumulates in abundance. These areas offer good protection for Foraminifera because of the absence of strong currents and possible nectonic predators. Very little movement occurs that would tend to crush or destroy fragile tests. The tides which submerge the high marsh carry with them considerable detritus which may include Foraminifera. These grass areas are excellent settling ground for any material which is suspended in the water, as shown by Shaler (1886). The tough stemmed grasses have a dampening effect on any incoming currents and much of the suspended material settles out.

It is probable that the high populations of Foraminifera are not washed in by highest tide but reproduce and grow in the high marsh. The forms found are very well developed, and few broken shells are found as may be expected if most of them are transported by currents for any distance. It seems improbable that so few inundations of the high marshes would account for such concentrated populations if they were transported and deposited in that environment. The restriction of 3 species to this habitat strongly suggests that it is an indigenous fauna.

It is interesting to note the contrast between total populations at the stations of traverses 1 and 2 in the marsh area; the largest total populations occur in traverse 1. The position of traverse 1 can be correlated approximately with the extreme limit of the Cape Cod Bay water as it enters the harbor on the incoming tide. It is at this line that the mass of bay water has its lowest velocity during late flood tide and the line where the greatest amount of settling of suspended material occurs.

Stations H1, H2, H3, H8, and H9 have faunas apparently anomalous for their subfacies. Station H1 is in an intertidal

flat close to the channel and its population is similar to the fauna of channel stations. The intertidal flats shift continuously, as do the channels, and it is not unexpected to find faunal mixing. Similar conditions exist at stations H2 and H3 in the *Spartina glabra* zone. These stations are located on sandy islands subject to changes by tidal current action and surrounded by channels, and small total populations are expected. Station H8, although in the intertidal flat zone, has a relatively high total population. It is located at the boundary between the marsh and an intertidal flat and its population is very similar to that of the high marsh areas. Station H9 was taken at the boundary between the high marsh and the dunes of Sandy Neck. This area is above water except during extremely high tides and it is in an area where there is subsurface fresh water seepage from the sand dunes; a small total population may be expected under such conditions.

Sediments at the channel stations are fine sand to coarse sand and contain little organic material. The sediments are related to strong currents along the channels during late ebb tide. Sediments of the intertidal flats are sand and silt with shell fragments and contain little organic material. The broken shells appear to be a result of the shifting sand of the intertidal flats crushing shells deposited there by flood tides. The sediments of the high marsh areas are composed of fine silt and rather coarse sand and have a high organic content. These sediments are composed of wind-blown sand from the dunes and fine silt washed up by tidal action and settled out of the water as indicated above. On a windy day the amount of wind-blown sand being deposited in these marsh areas is quite noticeable.

Salinity variations are not as great as would be expected in the harbor area. When the high marsh is covered by highest tides the water has a salinity range of 31.5°/00 to 32°/00. Under normal tidal conditions, however, these areas are wetted from underneath by water with the same salinity range as that of the intertidal flat zones, 25°/00 to 31°/00. These are maximum and minimum ranges and under normal tidal conditions the salinity range is approximately 28°/00 to 31°/00 on the intertidal flats. The channel stations at the head of the harbor (H22, H23, and H24) show the greatest salinity variation ranging from 20°/00 after a period of heavy pre-

cipitation and on the ebb tide to 31.5°/00 under normal conditions. Stations H14 and H15 at the mouth of the Harbor have salinity ranges of 31°/00 to 32°/00. The rest of the channel stations, H16, H17, H18, H19, H20, H21, all have about the same salinity range of 27.5°/00 to 31.5°/00.

Considerable work has been done on the productivity of the water of Barnstable Harbor by J. C. Ayers (personal communication). It has been found that the carbon content of the water varies from .0-.1 mgms./liter at the mouth of the harbor to .1-1 mgms./liter at the head of the harbor. This can be correlated with areas of greatest total Foraminifera populations which occur in traverse 1 in the harbor in the area where the water has the highest organic production.

The water temperatures of Barnstable Harbor are characterized as follows by J. C. Ayers (personal communication):

"Like most estuaries Barnstable Harbor warms the tidal water which enters it during the spring and summer and cools the entering tidal water during the fall and winter. Transition periods between warming and cooling occur twice a year, generally in March-April and in September-October. During these periods there is no horizontal temperature gradient along the length of the harbor. During the spring and summer there is a temperature difference between the head of the harbor and the harbor mouth of about 10°F. The incoming water at each point averages around 70°F., while the water at the head of the harbor averages about 80°F. These figures are for low tide when the greatest temperature differences occur. During the fall and winter the gradient from mouth to harbor head is about 5°F. At low tide in these seasons water in the head of the harbor is about 35°F. while at Beach Point, about 40°F."

The two Foraminifera subfacies of the bay areas can be correlated with the mud line. The nearshore sediments are composed of fine to coarse clean sand in water shallower than approximately 20 m. At approximately 20 m. the sediments become silty and grade into mud and sand, or mud, which continues offshore to a water depth of approximately 32 m. The greatest number of species and the largest populations occur in the deeper facies. The distribution of the Foraminifera from all stations deeper than 20 m. is fairly constant.

The salinity of the bay water is approximately 31°/00 to 32°/00 and remains fairly constant. The temperature cycle of Cape Cod Bay water is typical for nearshore water in cool temperate latitudes. Temperature data on the bay water in this area have been taken from the files of the Woods Hole Oceanographic Institution and are listed below. Temperatures are given in degrees Fahrenheit.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Om.	32.5	34.1	35.9	42.6	50.5	59.4	65.5	64.9	64.0	55.3	48.8	42.3
15 m.	——	34.9	34.9	42.3	45.9	54.9	——	58.7	58.0	55.1	48.8	42.3

It is quite apparent that temperature is relatively unimportant as an ecological factor affecting the distribution of Foraminifera within this part of Cape Cod Bay except that all the populations are of a cool temperate type. The maximum summer water temperature within Barnstable Harbor is higher than in Cape Cod Bay; this may be an ecologic factor of importance in causing differences in the Foraminifera facies of the harbor and the bay areas. Minimum salinity ranges within the harbor are an additional ecological factor which probably influences the differences between harbor and bay facies. In the Barnstable Harbor area the subfacies mainly are to be correlated with effects of tidal action or movement of bottom materials, degree of wetting provided, and organic production. Subfacies within the bay are to be correlated with the type of bottom material and thus the intensity of current and wave agitation of the bottom.

The desirability of more detailed study in this area is evident. It is important to obtain data on distribution of living Foraminifera to determine how much mixing of faunas is caused by tidal currents. There are numerous salt water marshes along the shoreline of Cape Cod and the adjacent New England coast which have environmental conditions similar to those of Barnstable Harbor. It is suggested that detailed studies be made of some of these marshes, analyzing surface distribution of Foraminifera faunas and also their vertical distribution in cores taken from the marshes. It is probable that similar faunal facies will be found in marshes in the New England region and elsewhere. It should be possible to reconstruct the detailed history of an old marsh area on the basis of Foraminifera.

CONCLUSIONS

(1) Barnstable Harbor contains a Foraminifera facies characterized by abundance of *Trochammina inflata* and related species. This is distinct from the adjacent nearshore Cape Cod facies which is characterized by *Proteonina atlantica* and *Eggerella advena*. Temperature and salinity differences are important ecologic factors in this distribution.

(2) There are at least 3 subfacies in Barnstable Harbor, developed on the high marsh, the intertidal flats, and in the channels. Distribution of these subfacies appears related to diurnal tidal action, nature and movement of bottom materials, presence of marsh grass and relative organic production.

(3) In Cape Cod Bay there is a nearshore Foraminifera subfacies, developed on sand bottom. A subfacies occurs offshore from the sand area which is in mud and sand or mud and is especially characterized by species of *Reophax*.

(4) The largest Foraminifera population occurs in Barnstable Harbor in the high marsh where there is the highest total organic production.

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REVIEW

The Meaning of Evolution; by GEORGE GAYLORD SIMPSON. Pp. xv, 364; 38 text figs. New Haven, 1949 (Yale University Press, $3.75).—This penetrating analysis of the course of organic evolution and of the causes underlying it, followed by an attempt to find therein some basis for human ethics and morality, is an amplification of the Terry Lectures delivered at Yale University in 1948. Accepting the factual truth of evolution as well established, Dr. Simpson presents a condensed yet comprehensive outline of the known history of life and a new analysis of its underlying principles. Aside from a tendency toward increase in the total amount of living matter, the course of evolution seems largely random and opportunistic. Oriented segments of evolutionary lines provide a crucial test for materialistic, vitalistic, and finalistic theories of the cause of evolution. Adaptation, which has a known mechanism in the action of natural selection upon the genetics of populations, is found to be the orienting factor in all real trends; hereditary changes have no direct relationship to the needs of animals or their opportunities for evolution; they provide an explanation for the randomness of evolution whereas natural selection resulting in adaptation is the orienting force. Non-adaptive changes are possible and may lead to the formation of higher systematic groups; such evolution is likely to be more rapid than normal, but is still the result of the same forces. Progress is not a universal feature of evolution; many criteria of progress are possible and each of them gives a branching pattern rather than a single line succession of types. By most but not all criteria man stands at the top of the animal kingdom. The history of life is flatly inconsistent with vitalism and finalism.

Man is a unique animal which has added a new type of evolution, based on the transmission and inheritance of learning, to the older organic evolution. This new evolution follows different laws and is subject to conscious control. However man and his unique attributes have arisen entirely through the materialistic operation of organic evolution. Man is not the goal of evolution, which was not planned.

Intuitive and naturalistic attempts to discover an absolute ethic have failed because ethics are relative and arose only with man. An ethic cannot automatically arise from the principles of organic evolution, but must be the result of rational choice. Knowledge and its transmission are the most basic features of the new, human evolution; promotion of knowledge is held to be good, for mankind, and is taken as a basic ethical proposition. The possession of knowledge and power of choice by man entail responsibility, and

the highest and most essential moral standards are involved in the fact of man's personal responsibility. Ethics based on these propositions are applied to a variety of human situations.

Evolution will continue. Man may bring about his own extinction, but he has the power to guide his own evolution and also that of other organisms. So long as human beings exist, there is no danger of a comparable animal arising to compete with them. Guidance of social evolution involves choice of ethical standards; the choice can be such that the evolution of mankind will be upward.

The agreeable ethical conclusions which Dr. Simpson derives from his study of evolution seem better grounded than earlier attempts along this line. One may suspect that his attack on the notions of a "struggle for existence" as an important part of the selection mechanism was influenced by a desire to eliminate the "tooth and claw" ethic which has been drawn therefrom; yet by his own premises that pre-human evolution was amoral and that ethics must apply specifically to mankind, such an ethic can be eliminated and the mechanism of selection has no bearing on the ethic of knowledge which he develops. Natural Selection, as Simpson says, is a matter of differential reproduction, but it seems to the reviewer that the success of each individual in coping with its environment for survival up to the time of reproduction—which is the essence of Darwin's statement—is a major determinant of which shall be able to reproduce.

The work as a whole is extremely readable, smooth in style, and with a minimum of technical jargon. It is legibly printed for the most part, but some charts have been reduced too much for clarity. The chart of the reptilian Orders has the Cenozoic Era spread out to greater length than the much longer time from Pennsylvanian to Cretaceous, which gives an illusion of excessive longevity to the survivors of the Mesozoic reptilian radiation. Full appreciation of the interpretive chapters in the second section of the book requires a greater knowledge of biology than the outline presented affords, but the central arguments can be followed by any educated reader. Results of recent advances in evolutionary theory are brought together in more condensed form, and frequently are more clearly stated than they have been hitherto; for this reason alone the book should be of value to every biologist.

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THE NOMENCLATURE AND CLASSIFICATION OF SEDIMENTARY ROCKS

JOHN RODGERS

ABSTRACT. According to the purposes they serve, classifications of sedimentary rocks may be classified into descriptive and genetic, and these further into purely descriptive and analytical descriptive classifications and into purely genetic and operational genetic classifications. No one classification can serve all purposes; at the least a descriptive and a genetic classification are needed. Moreover, field workers need primarily a purely descriptive classification and laboratory workers an analytical descriptive classification. A field classification might well be built around the recommendations of the Committee on Sedimentation of the National Research Council. For a laboratory classification, the confused state of igneous rock terminology warns against the pigeon-hole type of classification. It is suggested that a continuous variable type of classification, expressed entirely by measured parameters instead of rock names, would provide precise and objective designation of rocks in terms of their properties. The paper makes no attempt to present a detailed classification but is intended to stir up discussion of the principles of classification from which, later, general agreement may emerge.

INTRODUCTION

THE subject of classification is always a live one in geology, and the classification of sedimentary rocks is being especially debated at present, as witness the symposium recently published in the Journal of Geology (Pettijohn, 1948; Shrock, 1948; Krynine, 1948). All seem agreed that the existing classification is unsatisfactory, but there agreement ceases. The wide present interest insures, however, that all attempts to create new classifications will be subjected to many-sided analysis, and we may confidently expect that from this analysis a more satisfactory classification will ultimately emerge. The present paper is intended as a contribution to that analysis of classifications; it hopes to focus attention on certain points that may deserve consideration as we work at constructing a satisfactory scheme. The paper has benefitted greatly by the helpful criticisms of Adolph Knopf, Eleanora B. Knopf, Carl

O. Dunbar, and Richard F. Flint, but I must be held accountable for all that is crude, unclear, or simply erroneous in it.

The problem of classification inevitably entails the problem of terminology or nomenclature; indeed they are but facets of a single problem. Most scientific names imply a classification, whether actually carried through or no, and many classifications consist simply in the systematic arrangement of preexisting names. I shall assume therefore that the purposes served by nomenclatures are in general the same as those served by classification, and I shall begin by discussing the several purposes of sedimentary rock classifications.

KINDS OF CLASSIFICATIONS

The first purpose to be served by a nomenclature or classification of sedimentary rocks is to provide terms that will convey from one geological mind to another an adequate conception of the physical character of a given rock. To fulfill this purpose, the terms should be descriptive, objective, and precise; genetic terms, such as till, should be avoided because they depend on hypotheses of origin and are not necessary to convey the description. A classification that serves this purpose may be called a *descriptive* classification.

A descriptive classification should provide categories for rocks of every kind, thus facilitating for teacher and student a survey of all the possible varieties that may be encountered. But in addition the classification can be of great value to the research investigator if, by grouping the like and separating the unlike, it calls attention to genetically significant correlations between likenesses and unlikenesses. The properties that might be chosen for analyzing the relationships of phenomena as complex as sedimentary rocks are of course legion, but what distinguishes a good classification of this sort from a poor one is that the properties chosen are those that best bring out such correlations and thus lead toward genetic understanding of the phenomena. In such a classification a neat balance must be struck between the descriptive and the genetic; genetic terms as such must be avoided because they beg the question and prejudge interpretation of the observed correlations, but those descriptive terms that have in fact the highest correlation with genesis will make possible the most fruitful analysis. A

descriptive classification that serves this additional purpose may be called an ***analytical*** descriptive classification.

A quite different purpose that may be served by a classification of sedimentary rocks is to provide terms that will convey from one mind to another an adequate conception of what is known, inferred, or believed to be the origin of a given rock. To fulfill this purpose, the terms should be genetic and unequivocal; terms that indicate the origin directly, such as till, are preferable to terms that do not, such as boulder clay. A classification that serves this purpose may be called a ***genetic*** classification.

A genetic classification should provide categories for rocks of every origin, thus facilitating for teacher and student a survey of all the possible hypotheses that may need to be considered. But in addition, the classification can be of great value to the research investigator if it calls attention to genetically significant criteria that may be applied in specific instances. The criteria that might serve as a basis for classifying such complex phenomena by origin are legion, but what distinguishes a good classification of this sort from a poor one is that the criteria chosen are such that the investigator can observe them unequivocally in the data available to him. To borrow a word from the jargon of the methodologists, such criteria are "operational." Here again a nice balance must be struck between the genetic and the descriptive; those genetic traits that have the highest correlation with descriptive data will provide the most useful "operational" criteria. A genetic classification that serves this additional purpose may be called an *operational* genetic classification.

Clearly the analytical and the operational classifications approach each other, and when every fact is known and every interpretation secure they will coincide to form the ideal classification toward which we are striving. But until that happy day (when all of us in sedimentary geology will be looking for other jobs), no one classification can serve all the purposes enumerated, and a classification satisfactory for one purpose, such as description, will necessarily be less than satisfactory for others, such as expressing origin. To repeat the example already mentioned, the term till gives a clear conception of the genesis of the material it refers to, but it does not provide an adequate description of that material, which might

be a strongly cohesive boulder-bearing clay, a compact but weakly cohesive silty clay with scattered chalk fragments, or a loose silty and sandy rubble. Moreover, if it is not known whether the material in question was deposited by ice or by mudflow, the genetic term cannot properly be applied and if applied will be misleading, but an objective description is still valid. On the other hand, the genetic classification conveys readily whatever can be inferred about the origin of the material and is especially helpful in suggesting additional relationships that may be looked for in checking the original inference; few if any purely descriptive classifications can accomplish this end.

For sedimentary rocks then at least two types of classification are needed, the descriptive and the genetic; neither will suffice alone. The use of descriptive terms alone would indeed make sedimentary geology a dull and mechanical subject, leading to little understanding of phenomena and hardly deserving the name of science. On the other hand, the use of genetic terms alone is not dull but dangerous; for once a term is attached to a given rock it tends to conceal ignorance and discourage re-examination, yet one of the cardinal principles of the scientific method is that no hypothesis, theory, or law shall ever be so firmly established and enshrined that it is secure from restudy, reappraisal, and perhaps rejection, whenever new facts are discovered that appear to conflict with it. If, however, the descriptive classification used is in addition analytical, then the dull process of cataloguing rock types is given point and significance and helps us to understand those types; if the genetic classification used is operational, the dangerous tendency to theorize beyond the data can be kept in check by frequent reference to objective facts. In the present imperfect state of knowledge, both classifications are needed, and neither should usurp the place of the other.

I must therefore protest vigorously against such statements as "There can be no such [descriptive] classification worthy of consideration" (Pettijohn, 1948, p. 113). Yet to quote this one statement out of context is quite unfair, for Pettijohn in the passage cited is pleading in fact for a classification in which "the characters used for the classification are meaningful or significant." To me, however, such a classi-

fication is not properly a genetic classification, as he seems to imply, but rather one of the type to which the term analytical was applied above. Pettijohn notes that the igneous petrologists do not classify their rocks by color, but he fails to note that they do classify them by such purely descriptive characters as grain size, mineral content, and feldspar composition, and in general have stopped classifying igneous rocks according to whether they are Paleozoic or Cenozoic and are tending away from the older subdivision into deepseated, hypabyssal, and volcanic. Feldspar composition seems a better basis than color because it appears to be of more genetic significance, but nevertheless the classification is strictly descriptive. That a purely genetic classification has value, I would be the last to deny, but I would suggest that the problem of genetic classification should be kept quite separate from that of descriptive classification, and furthermore that the first order of business for sedimentary geologists at the moment is to reach agreement on a satisfactory descriptive and preferably an analytical classification of our rocks.

EXISTING CLASSIFICATIONS

A touchstone for evaluating classifications of sedimentary rocks is provided by the rocks commonly grouped as limestone, for these rocks display an overall descriptive homogeneity, as shown by the use of a single field term for them, but are genetically varied. It is of some interest, therefore, to examine the disposition of these rocks in some of the principal classifications that have been proposed to replace the conventional subdivision of the sedimentary rocks.

The most uncompromisingly genetic classification ever proposed is that set forth by Grabau in his Principles of Stratigraphy (Grabau, 1913), and his treatment of limestone illustrates this very well. As Professor H. Ries once pointed out to me, the word limestone does not even appear in the index of the book, the rocks in question are scattered through four or five major subdivisions of the classification, and they bear a variety of names such as calcilutyte, hydrogranulyte, biopulveryte, etc. As a genetic classification, this is thoroughly logical, but a student wishing to learn about the rocks usually called limestone or to run down the origin of a particular one will find

it of little use. For the most part operational criteria are lacking, and the classification has been largely ignored.

In recent textbooks and articles, other classifications have been proposed as genetic by Hatch, Rastall, and Black (1938, pp. 36-39, 152), by Twenhofel (1939, pp. 260-261), and by Shrock (1948, pp. 118-119). All of these writers state that the rocks called limestone are diverse genetically, yet all of them actually group them into a single category. Surely these classifications are not genetic at all but descriptive classifications masquerading as genetic or possessing genetic subcategories, thus mixing genetic and descriptive in unsystematic fashion, and they do not differ in any essentials from the conventional classification found in most elementary textbooks of geology.

A quite different approach is that of Krynine (1948, esp. pp. 147-149), who in contrast to the men just mentioned proposes a frankly descriptive field classification. Krynine makes it evident however that he is not content with a *purely* descriptive classification but is constructing one that in the terminology suggested in this paper is analytical. This approach he applies in the first instance to the subdivision of sandstone, and one does not have to believe that there is 100 percent or even 80 percent correlation between, for instance, arkose and extreme uplift to see the great value of the method. Krynine then applies the same subdivisions to the other main groups of sedimentary rocks. Limestone he divides on two bases; first on the presence or absence of 5 percent or more of recognizably fragmental non-calcareous material and of 10 percent or more of recognizably fragmental calcareous material, second on the mineral composition of the non-calcareous fragmental fraction, using the same subdivisions as for sandstone.

This second basis seems rather less significant for limestone than for sandstone, for it depends on a minor constituent of the rock and, as pointed out to me by John A. Elson, Krynine admits it will often require studying an insoluble residue, hardly a field procedure. The first basis on the other hand might be expanded (though perhaps not in a field classification) by recognizing subdivisions based on the dominance or relative proportions in the calcareous fraction of the following four components: non-fragmental recognizably organic material,

recognizably organic fragments, inorganic fragments, apparently inorganic and non-fragmental material (which might be either the result of direct chemical precipitation or of thorough recrystallization, a distinction for which we have as yet no good operational criterion). But details are of minor importance compared with the principle to which Krynine has adhered, that of selecting as the basis of classification objective and descriptive characters, but those that have the highest correlation with genesis. Krynine's classification thus possesses a vitality that Grabau's lacked, and many of his proposals will almost certainly find their way into the classification toward which we are all working.

SUGGESTIONS FOR FUTURE CLASSIFICATIONS

Krynine's paper underlines another problem that faces the maker of classifications, the conflict between the needs of the field and the laboratory worker. The need of the field man is primarily for a purely descriptive classification, by which he can convey clearly, precisely, and objectively what he sees. Hence a field classification is more likely to use obvious characters than less obvious but genetically more significant ones. That the tendency to record obvious characters only and to ignore all the others has been overdone cannot be gainsaid, and it diminishes greatly the value of many field reports, but the field man commonly has many things to observe in a limited time beside the details of sedimentary rocks, and if the classification is too complicated or difficult he simply will not use it at all. In contrast, the laboratory worker is ordinarily primarily interested in genetic understanding, and the best *descriptive* classification for him (I leave to one side genetic classification) is an analytical one. Moreover, he is presumably equipped to determine any determinable character, and his only concern is not to waste time determining characters that have no significance. For him, therefore, it does not matter how subtle the characters used in classification are but only whether they have a high correlation with genesis; in other words, the more analytical the classification the better.

For a field classification, I would like to call attention to the classification set forth in a series of reports to the Committee on Sedimentation of the National Research Council (Went-

worth and Williams, 1932; Wentworth, 1935; Allen, 1936; Twenhofel, 1937; Tarr, 1938). Here is a classification beaten out after considerable thought and consultation among sedimentary geologists and providing for the most part simple but quantitative definitions of descriptive rock terms (a number of convenient genetic terms are also defined). The classification has no overall guiding principle except convenience and a proper respect for the coiners of terms, but it may be questioned whether phenomena as complex as sedimentary rocks will yield to any single-track classification. Probably no one will agree with all of the classification; for instance I object to the extension of the term mudstone to include not only all consolidated but all unconsolidated fragmental sediments with particles less than 1/16 mm., as I prefer the commoner restriction to a consolidated rock in that range which does *not* show fissility, but as pointed out to me by R. R. Shrock, this is not the original definition of the term, and perhaps it has been used in so many senses that it should be abandoned. Admittedly also the classification fails the limestone test miserably, for the Committee never made a proposal for the nomenclature of the carbonate rocks. But this gap could readily be filled along the lines of the existing classification; as a basis for discussion I venture to suggest a primary distinction between limestone (made of calcite) and dolomite[1]; a secondary distinction between carbonate rock made principally of organic material and that made principally of inorganic or indeterminable material; further distinction in the organic carbonate rocks according to the dominant organism, if recognizable, and according to whether the organic remains are roughly in place and whole (as in a coral reef) or mechanically transported and fragmental, if that can be determined; and further distinction in the inorganic carbonate rocks according to the presence or absence of recognizable fragmental grains or mechanical structure (such as cross lamination) and according to grain-size. In any case, the Committee recommendations could be made the basis for future discussions of a descriptive

[1] Dolostone (Shrock, 1948, p. 126) seems unnecessary, as the term dolomite was first proposed (in the form dolomie) by de Saussure fils (1792) for the rock; Dolomieu (1791) and both de Saussures (1792; 1796, pp. 17, 109, 110) write "pierre" repeatedly. As the mineralogists are the ones who have duplicated the term, they might choose some variant, such as dolomine.

field classification of sedimentary rocks, and we could attempt to sharpen up the Committee classification and fill in its gaps rather than try to start from scratch and convert the field geologist to radically new usages.

For a laboratory classification, I have no complete classification to offer, only a few negative remarks to make. Such a classification could demand relatively complete information on all the important measurable properties of sediments, and hence could use any of these properties for its subdivisions. The prevailing theory of classification seems to be to set up named compartments, quantitatively defined of course, in a grid system of 2, 3, or more dimensions, each dimension being a different parameter. If I might be facetious, I would christen a classification of this type a pigeonhole classification. Pettijohn seems to advocate (1948, p. 114) the ultimate in this type, in which each important rock type would receive its own separate name, commonly geographical; for example, bradfordite for sandstone like the one described by Krynine (1940) from well samples of an oil sand in the Bradford district, and spergenite for rock like the familiar Indiana building stone. Pettijohn points to the analogous terminology of igneous rocks, but surely the condition of igneous rock nomenclature should be a warning to the sedimentary geologists rather than a guide. The number of individual rock names for igneous rocks that had been coined before 1935 was 900 or more (Tröger, 1935, pp. 3-5), and few of these give in themselves a hint as to the kind of rock denominated. Among the igneous geologists themselves there is a growing dissatisfaction with the whole haphazard and unwieldy scheme and the burden it places on the memory (for a recent searching criticism, see Shand, 1944). In view of the unhappy experience of our colleagues, we sedimentary geologists would do well to forego the heady wine of indiscriminate name-giving (and credit-claiming) in order to avoid the hangover of a confused and illogical terminology.

As a counter to the pigeonhole type, I would like to suggest what might be called the continuous variable type of classification. An example in another field would be the modern description of the plagioclase feldspars. During the earlier period of study of the feldspars, a number of different mineral species were recognized within the plagioclase series and each was given

a name. With more study it became clear that the series is continuous from albite to anorthite, and the usage of these names was standardized to imply fixed quantitative limits, but at the same time an alternative system of designation was adopted based on percentage composition in terms of "end members." Thus a given feldspar may be described by the term oligoclase or by the symbol $Ab_{89}An_{11}$ (note that Ab and An do not stand for the *minerals* albite and anorthite but for chemical abstractions). Of these, the latter is not only shorter, but a great deal more precise. Moreover, the use of species names unduly emphasizes artificial boundaries. Why, for instance, should $Ab_{89}An_{11}$ and $Ab_{71}An_{29}$ be grouped together as oligoclase but $An_{89}An_{11}$ and $Ab_{91}An_{9}$, which are clearly more closely related, be separated as though quite different? In the case of the feldspars no one is likely to be misled, but according to several igneous rock classifications, the same distinction may cause two rocks to be separated as soda granite and granodiorite, though the entire difference between them is 2 percent in the composition of the plagioclase feldspar.

It will be objected that boundaries, even though necessarily arbitrary, are essential. But why? The rocks we are dealing with show a continuous range in most of the variables we can measure, and a classification that faces and makes use of that fact should be more useful than one that overlooks and distorts it. To be sure, we may well find breaks in such ranges that will give a basis for "natural" boundaries between classes of rocks. But in most quantitative schemes of classification, the boundaries are set up first, mainly with a view to a symmetry which the rock distribution itself does not possess, and the rocks are then expected to fit the neat pigeonholes. This is no criticism of quantitative classification as such, but only of the pigeonhole type; for example, the pigeonholes, the grads and rangs, of the C.I.P.W. system are dead and forgotten, but the continuous variable system on which they were based, the norm, is still widely used in igneous geology.

Defenders of the pigeonholes will point, however, to the convenience of group terms such as basalt, diorite, granite, for conveying the general character of the rock, which is after all the first purpose of classification as mentioned at the beginning of this paper. But that purpose is especially the province of

the field classification; the purpose of the laboratory classification is to convey not general but precise information, such as can be obtained by laboratory techniques. And again the constant confusion between field and laboratory terms for igneous rocks should give sedimentary geologists pause. It is often very difficult to tell whether, in a given paper, the term granite is being used in the precise laboratory sense of a rock consisting largely of potassian feldspar (according to some classifications it might be albite) with more than 10 percent quartz, or in the broad field sense of any light-colored coarse-grained quartzose rock. Thus we read again and again of the great granite batholiths of the Cordillera, most of which consist primarily of quartz monzonite and granodiorite. We can avoid this confusion in sedimentary geology if we will restrict the older terms such as sandstone, shale, limestone to the field classification and construct the laboratory classification on a new basis. For that basis I would like to suggest the measurement of basic parameters and their expression in formulae like those for the feldspars. Instead of first getting up our own categories and confidently pigeonholing the rocks in this one or that one, let us first study and measure the rocks and plot the measurements on triangular diagrams and other graphs, and then look diffidently to see whether there are natural groupings of those rocks that might deserve special terms.

There have been certain attempts of this sort already. I think first of Alling's paper on "microlithologies" (1945), which frankly proposes a laboratory classification of rocks without reference to the usual field terms. The classification is based on a triangular diagram, the end members of which represent the argillaceous, calcareous, and siliceous fractions of the rock, computed according to certain quantitative rules. Thus a rock called in the field a limy shale might be designated by the formula $A_{70}C_{25}S_5$. Alling has marred his own case by permitting such quantitatively meaningless expressions as "5 to 10 percent of the clastic carbonate" (p. 745) to slip in (cf. also the entirely qualitative and therefore quite unreproducible description of types of fissility, p. 753), but no one who has struggled with facies faunas can look at diagrams A and B of his figure 6 (p. 751) without realizing the power of the method.

A second proposal for the use of continuous variables in sedi-

mentary classification is that of Krumbein and his associates (Krumbein, 1948; Dapples, Krumbein, and Sloss, 1948). Krumbein also uses a triangular diagram and supplements it by ratios between the end members; these ratios permit the plotting of significant isopleth (isolith) lines on maps, as he has demonstrated. To be sure, points in his triangle refer not to individual sedimentary rocks but to summations of the rocks in stratigraphic sections of the order of magnitude of a system. The principle, however, could certainly be applied to the classification of rocks, provided the end members were quantitatively and operationally defined so that results could be reproduced from laboratory to laboratory.

Krumbein has also shown (1948, pp. 1916 ff., fig. 5) how readily the principle can be extended to all parts of a classification by subdividing each end member of the original triangle on additional triangular diagrams, and by adding additional triangles for other subdivisions, including genetic ones.

Similarly Krynine (1948, fig. 4) has illustrated the subdivision of sandstone on the basis of a triangle whose end members are mineralogically defined; thus a given sandstone might be designated as $Q_5A_{25}G_{70}$[2] (in Krynine's terms a high rank graywacke). (That his diagram shows arbitrary boundaries and that its end members are not quantitatively defined is irrelevant, for in the paper in question he was not proposing the triangle as a basis for a detailed laboratory classification but using it to illustrate the principles of his field classification.)

These examples indicate the form which a laboratory classification of the continuous variable type might take. The fundamental designation might well follow Alling's lead and be expressed in proportions of argillaceous, calcareous, siliceous, and other. Further distinctions could be based on subdivision of the dominant end members of any rock; thus the siliceous end member might be divided according to Krynine's scheme (as suggested by Krumbein, 1948, pp. 1917-1918, fig. 5), the argillaceous by the proportions of the main groups of clay minerals. Again subdivision might be made on grain size or on grain fabric, say the proportion of interlocking to non-interlocking (presumably fragmental) borders. Subdivision into three end members at each step has, of course, no special magic

[2] Standing for quartzite, arkose, and graywacke.

virtue; two or four components might be called for at various steps. (Four components can be handled on triangular diagrams by replacing the point that expresses three components by a small triangle whose size is proportional to the amount of the fourth component, which should be the least important in the given group of data, or by indicating beside each point its altitude in the four-component tetrahedron of which the given triangular diagram is the base.) The most important requirement would be that each end member be simply, quantitatively, and if possible operationally defined, so that workers in different laboratories might arrive at comparable figures. A set of three or four formulae constructed in this fashion would indicate the composition and perhaps other characters of the rock in less space and with far greater precision than the conventional terms, even if there were general agreement on quantitative limits to the pigeonholes those terms represented. For example, the formula $A_{30}C_{0}S_{70}$; $Q_{15}A_{80}G_{5}$; $K_{90}M_{0}I_{10}$[8], plus a cumulative or frequency curve of the size distribution (or a statement of the first three moments) would describe a highly feldspathic non-calcareous arkose with abundant kaolinitic cement, and at the same time would indicate precisely where in the range of arkose the given rock would fall.

CONCLUDING REMARKS

In conclusion, I venture to sum up the suggestions made in this paper. Classifications of sedimentary rocks serve a number of purposes, and no one can serve all; we need both descriptive and genetic classifications, but the need for the former is at present the greater. Among descriptive classifications we need a purely descriptive classification for field use and an analytical descriptive classification for laboratory use. The field classification might well be built around the recommendations of the National Research Council Committee on Sedimentation. For the laboratory classification, I suggest abandoning the traditional pigeonhole type of classification and attempting to replace it with formulae of the continuous variable type which, although abstract, express the data precisely and without subjective coloration.

[8] Standing for kaolin group, montmorillonite group, and "illite" group of clay minerals.

Finally, I realize that many of the proposals here made are shots in the dark and require careful study and much modification before they can hope to be considered for acceptance. If this contribution has any value, it is likely to be negative, by leading to a review of the tacit assumptions and unquestioned procedures that have underlain our attempts at classification, rather than positive, by presenting fully blown the classification to end all classifications. I believe that no one of us alone can presume to create such an ideal classification for no one of us sees all the needs, those of the field man and those of the laboratory worker, those of the teacher and student and those of the research investigator. But by working together, by friendly interchange of ideas and constructive criticism, we should be able to devise a classification or rather classifications which if not satisfactory to all in all respects will at least provide us with an adequate common language.

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THE JADEITE PROBLEM

HATTEN S. YODER, JR.

PART II

PREVIOUS EXPERIMENTAL WORK

One of the early attempts to crystallize jadeite (Doelter, 1884, p. 63) yielded only a glass. In 1887 Lemberg subjected glasses, produced by melting natural jadeite, to solutions containing NaCl or Na_2CO_3 at several hundred degrees for long periods. In all cases analcite was produced. In 1903 Doelter gave the "melting point" of jadeite as 1000 to 1060°C. Schumoff-Deleano (1913) attempted to synthesize the crystals of the diopside-jadeite series using mixtures of synthetic diopside and a natural jadeite from "Tibet." She concluded that diopside suffered no change in optical properties when crystallized from a melt containing up to 5 per cent of the jadeite component. With a mixture containing greater than 5 per cent and less than 15 per cent, diopside crystals were obtained in a groundmass of diopside, jadeite, and glass. The jadeite in the groundmass was the remnants of the unmelted natural material. A mixture containing more than 15 per cent of jadeite yielded all glass. It was stated that jadeite had not been synthesized directly nor by using sodium tungstate, sodium molybdate, or other fluxes.

Scott (1916) in his study of analcite was unsuccessful in his attempt to verify Doelter's claim of preparing "anhydrous soda-leucite" by dry fusion. He found that a glass of the jadeite composition yielded nepheline and glass, or carnegieite and glass depending on the temperature of crystallization. He doubted if an anhydrous feldspathoid of the composition $NaAlSi_2O_6$ existed.

It should be mentioned here that the "decomposition" of leucite into nepheline and orthoclase (pseudoleucite) is *not* analogous to the assumed reaction 2Jd = Ne + Ab. Bowen and Ellestad (1937) have shown that pseudoleucite is produced as a result of the following reaction: leucite + liquid = nepheline + orthoclase.

In 1922 Eskola and Adams (unpublished), working at the Geophysical Laboratory, attempted to produce jadeite from a

synthetic glass under high hydrostatic pressures (less than 4000 atmospheres), but obtained only a feathery intergrowth which Merwin said might be or might not be jadeite. In experiments using the Morey-type bombs, Eskola obtained unidentifiable fibrous products. He (personal communication to Dr. Adams, 1948) is of the opinion that the formation of jadeite should be promoted by pressure, but perhaps mineralizers are also necessary to help crystallization.

Bowen (1922) published the pseudobinary diagram of equilibria for mixtures of nepheline and diopside (fig. 6). From

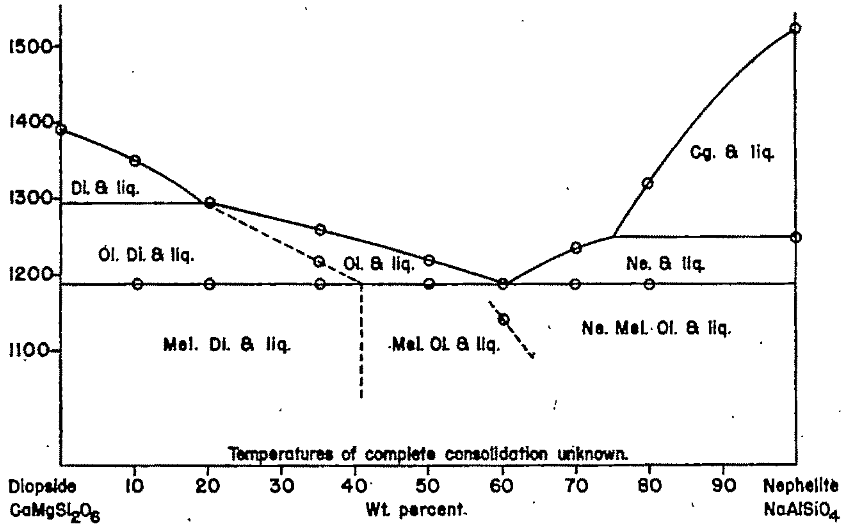

Fig. 6. Pseudobinary diagram of equilibria for mixtures of nepheline and diopside (Bowen, 1922).

these data and field observations in Quebec, he concluded that the residual nephelite-rich liquid could give rise to products of the analcite composition, i.e., jadeite.

Using the sealed capsule technique, Goranson (unpublished) in 1931 also tried to synthesize jadeite from a glass in the presence of water vapor. He recorded the following notes:

Original Material	Per cent H_2O in capsule	Products
1. Synthetic glass	4.26	glass + rod-like fibers and possibly plates. Negative elongation and extinction parallel to elongation.

2.	Synthetic glass	13.47	glass + numerous hexagonal plates of nepheline + rods of albite (?). Some of nepheline crystals appear altered.
3.	Burma jadeite	12.05	glass + crystalline material. Rods like in No. 1. Negative elongation.
4.	Burma jadeite	8.10	glass + crystalline material. Rods and possibly another phase.

These were held for three hours at 800 ± 10°C. under 2000 kg/cm^2 pressure. No jadeite was produced.

Greig and Barth (1938) determined the binary diagram, nepheline—albite (fig. 7), in which the composition of jadeite

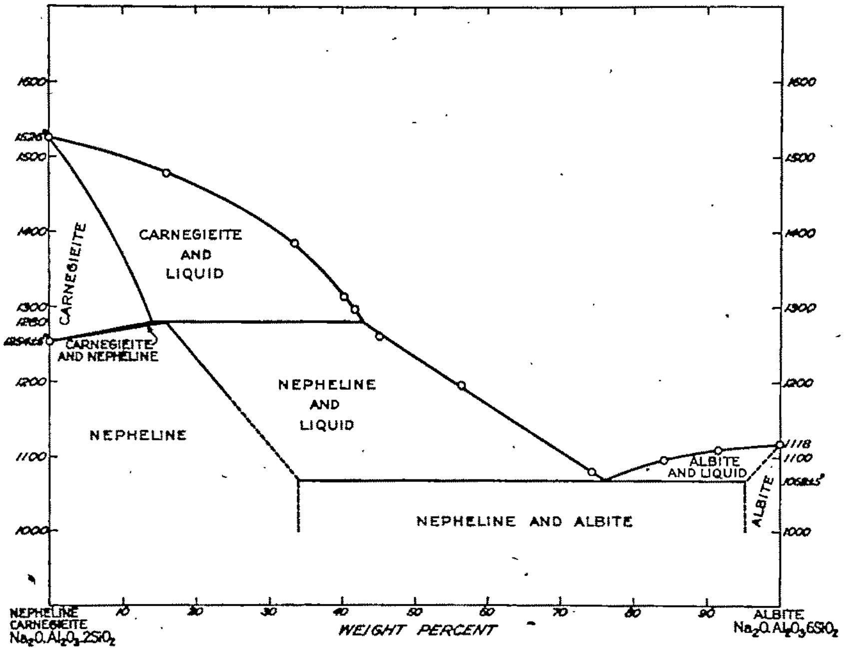

Fig. 7. Equilibrium diagram for the system, $NaAlSiO_4$ — $NaAlSi_3O_8$ (Greig and Barth).

occurs (Ne 35.14 per cent). No crystals of jadeite were found in any of the preparations. In an effort to decide whether jadeite was stable or not under the conditions of the experiment, they heated a natural jadeite from Burma (USNM #94303) and found that it decomposed as low as 800°C. After having been heated at 1015°C., the natural material was completely

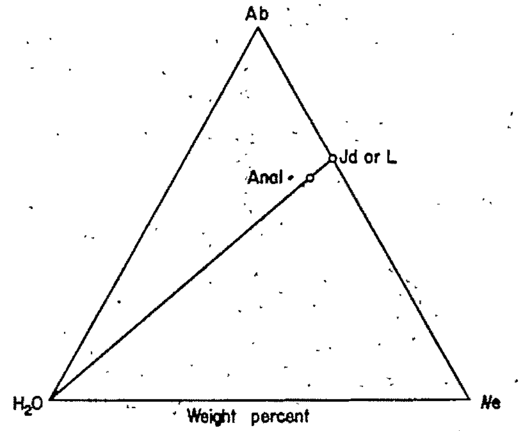

Fig. 8. The system, H_2O — Nepheline — Albite.

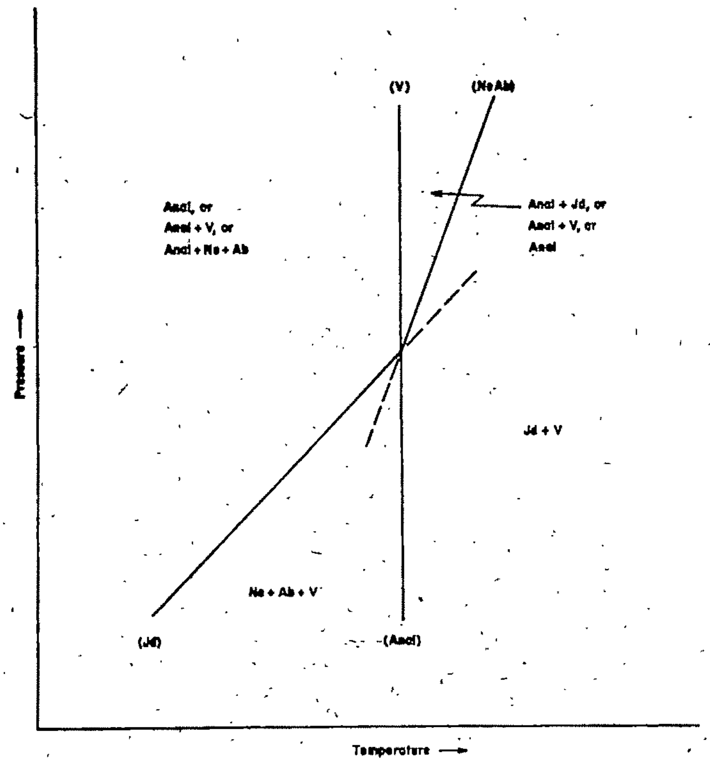

Fig. 9. Case I. Theoretical relations in the system, H_2O — Nepheline — Albite (after Morey).

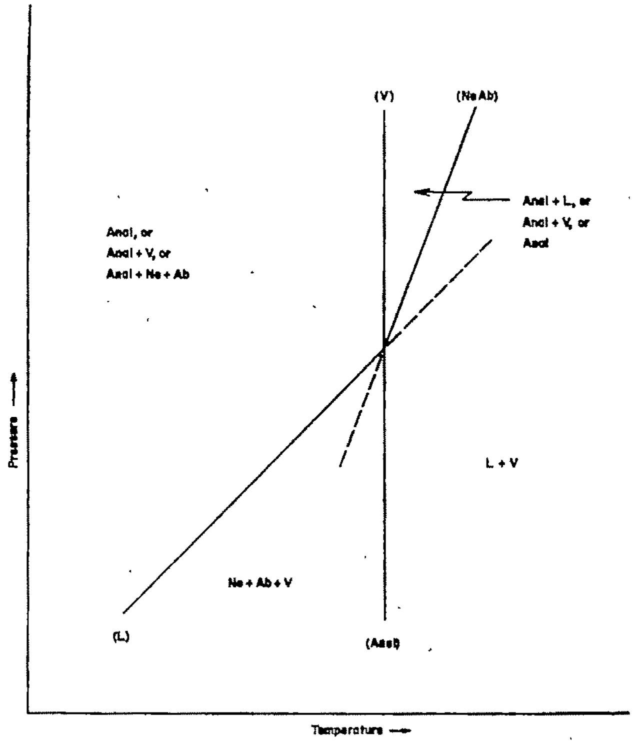

Fig. 10. Case II. Theoretical relations in the system, H_2O — Nepheline — Albite (after Morey).

changed to glass plus large nepheline crystals. They concluded that jadeite was not stable under the conditions of the experiment. The solidus temperature of the jadeite composition was fixed at 1068 ± 5°C. and the liquidus temperature at 1138°C.

Foster (1942) also failed to obtain jadeite in the system albite—wollastonite—nepheline. He said this was "compatible with the general belief that jadeite requires considerable pressure for its formation."

Morey (unpublished, 1947) subjected natural jadeite, analcite, and synthetic glass of the jadeite composition to 400°C. and approximately 1000 atmospheres water vapor for several days in the Morey-type bombs. The natural material was unchanged, the analcite was unchanged, and the glass had completely crystallized into analcite. From these and other experiments, Morey concluded that stable equilibrium had not

been obtained and therefore the results were inconclusive.

In addition to this experimental work, Morey made a detailed theoretical study of the system H_2O—nepheline—albite (fig. 8). He assumed that three components were sufficient to express the composition of all phases; that is, that all phases were in the plane H_2O—nepheline—albite, or H_2O—$Na_2O{\cdot}Al_2O_3$—SiO_2. The coexistence of four phases, therefore, would give a monovariant system represented by a curve on the P-T diagram. This curve would be terminated, according to Morey, at an invariant point at which another phase is formed. This phase may be either a solid or a liquid such as would be formed at a congruent or incongruent melting point, but it was assumed to be in the plane H_2O—nepheline—albite. The first case is given in figure 9 where the solid phase is assumed to be jadeite. Only compositions along the H_2O—jadeite join are considered here. The curves are designated by the phase absent; the fields by the possible combinations of phase present. From a qualitative approximation of the entropy and volume differences, it was shown by Morey that in this case a field of jadeite exists at atmospheric pressure; therefore jadeite cannot be considered as a pressure mineral. If a liquid, such as at a congruent melting point, is formed at the quintuple point, the picture becomes that of figure 10. Again only compositions along the H_2O—liquid join are considered, and the composition of the liquid is assumed to be that of jadeite. It should be noted that these are not the only possible relations in the system H_2O—nepheline—albite.

Bowen and Tuttle (unpublished, 1947), using the Tuttle quenching apparatus, subjected a synthetic glass of the jadeite composition to the following conditions.

58F	710°C.	15,000 psi	1 hr.	nepheline (?), albite, and glass. rare crystals.
59A	710	30,000	1	nepheline (less than 5 per cent) + albite (rare) + glass.
59C	610	30,000	2.5	nepheline + albite + glass. crystals less than 5 per cent.
59D	500	30,000	5	analcite 100 per cent.
59G	550	30,000	1	analcite 100 per cent.

While these experiments were in progress Schairer (unpublished, 1947) determined the liquidus conditions for the plane

diopside—nepheline—silica (fig. 11) and some of the relations in the pseudobinary system jadeite—diopside (fig. 12). In the latter system, the phases present below the liquidus were determined in part by x-ray diffraction powder patterns. The diopside—nepheline—silica diagram bears out the conclusions of Bowen (1922). It is significant that a mixture in the forsterite field can yield a residual liquid of approximately the jadeite composition. In the two known field occurrences of jadeite, the

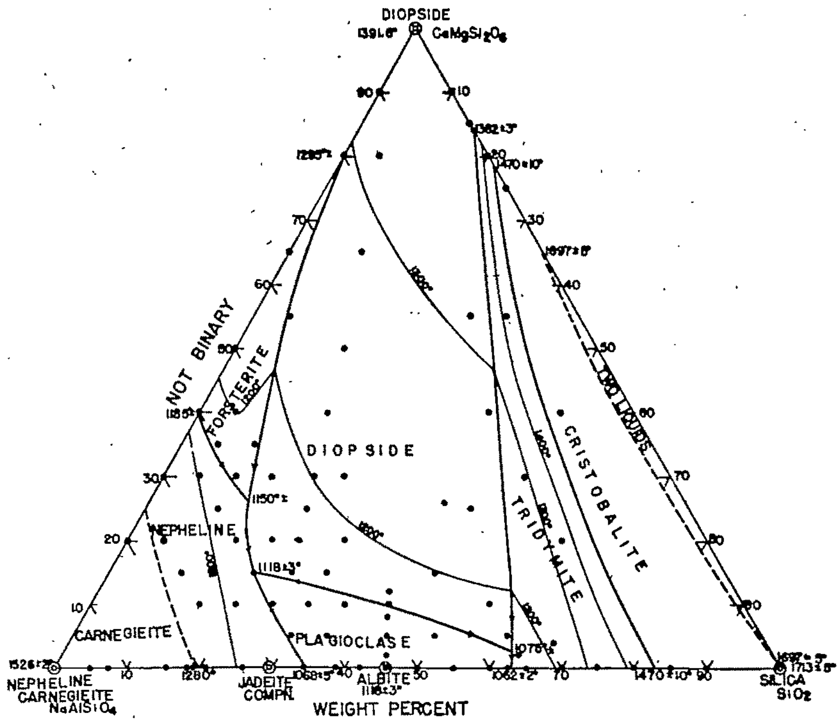

Fig. 11. Preliminary diagram of the system, $CaMgSi_2O_6$—$NaAlSiO_4$—SiO_2 (Schairer, unpublished).

pyroxene occurs in a serpentine. There is the suggestion, then, that the jadeite formed as a residual product of the process which gave rise to the serpentine. Bowen and Tuttle (1949) have fixed the upper limit of the field of stability of serpentine in the vicinity of 500°C. Jadeite, if this reasoning is correct, would have formed at a temperature less than 500°C.

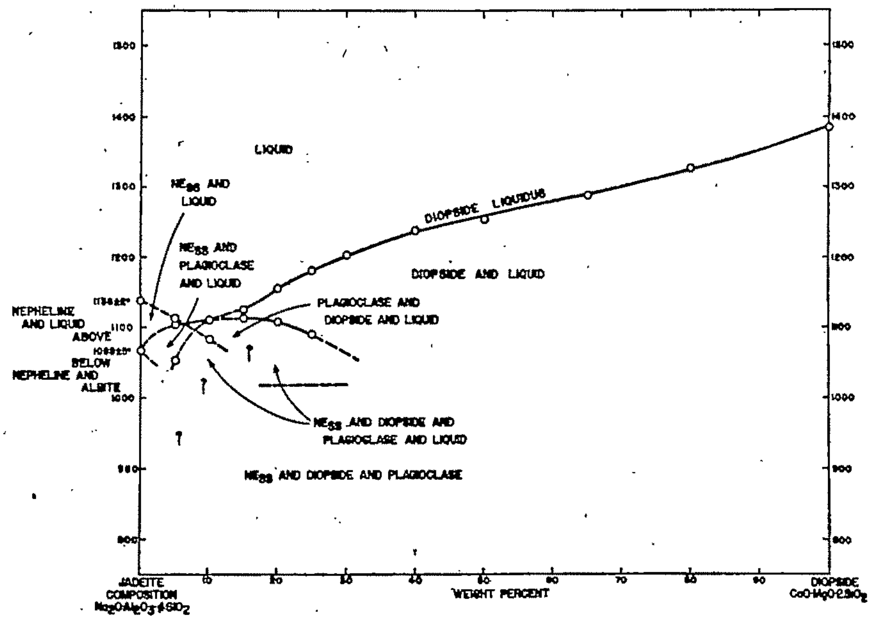

Fig. 12. Preliminary diagram of the join, Jadeite — Diopside (Schairer and Yoder, unpublished).

In addition, Schairer and Merwin (unpublished, 1948) investigated the decomposition of two natural jadeites from Burma (USNM #94829 and #94303). On the basis of heatings two weeks long they found that both specimens showed signs of decomposition into material of a lower index (less than 1.53) at a temperature as low as 850°C. The observation was made that the natural jadeite first melts completely metastably and then crystallizes into nepheline and albite. The liquidus temperature of the natural material (USNM #94829) was determined to be 1128°C. below which nepheline first forms.

Schairer and Yoder (unpublished, 1949) have also made exploratory runs on the jadeite—acmite join (fig. 13). All mixes at 800°C. which had completely crystallized contained acmite (or acmitic pyroxene), nepheline solid solutions, and albite. Present data indicate that there is a lowering of the incongruent melting point of acmite (990°C.). The phases present below the liquidus were determined in part by x-ray diffraction powder patterns.

Recent experiments of Bowen and Tuttle (unpublished, 1949) indicate that there are two forms of albite. Although they have not been able to synthesize the low form, there is evidence that the transformation takes place as low as 700°C.

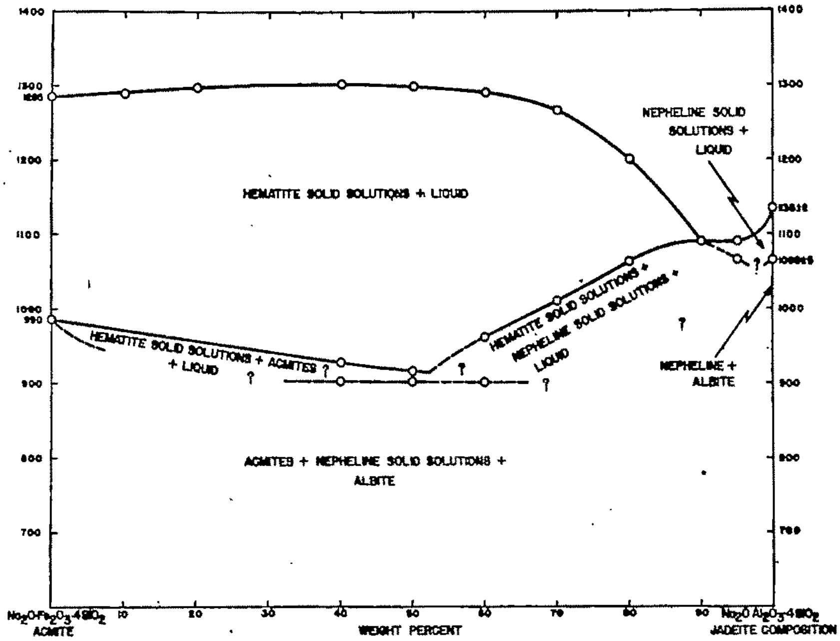

Fig. 13. Preliminary diagram of the join, Acmite — Jadeite (Schairer and Yoder, unpublished).

Tuttle examined a specimen of albite which contained some jadeite from Tasco, Querrero, Mexico, loaned to the writer by W. F. Foshag. The albite was of the low form such as is found at Amelia County, Virginia. This suggests that the jadeite may have formed at temperatures at least as low as 700°C.

FURTHER EXPERIMENTAL WORK

Thermal. Synthetic glass of the composition of jadeite ($n = 1.498$) was prepared for the writer by Dr. J. F. Schairer. The index agreed exactly with that obtained by Kani and Hosokawa (1936). Care was taken to anneal the glass at successively lower temperatures (to 1150°C.) with intermediate crushings. Such procedure was found helpful in increasing the rate

of crystallization of albite from its glass. The glass was then held for two months at 500, 600, 700, 800, 900, and 1000°C. At 800°C. and below the glass did not crystallize. At 900 and 1000°C. the glass crystallized into nepheline and albite.

Natural jadeite held at the same series of temperatures was unchanged at 800°C. and below. At 900 and 1000°C. it completely decomposed into nepheline and albite. This agrees with the shorter runs of Schairer on the same specimen.

Powders of the jadeite composition consisting of sodium carbonate, alumina, and quartz were pressed under five tons per square inch and sintered at the same series of temperatures. No change was observed at and below 800°C.; at 900 and 1000°C. small clusters of nepheline and albite were found to have grown about the grains of alumina.

Fluxes. Synthetic glass was heated at temperatures above the melting points of sodium metavanadate (630°), sodium tungstate (698°), and sodium molybdate (687°). In all cases nepheline and albite crystallized.

Volatiles. Small amounts of synthetic glass were placed in sealed silica tubes with a few grains of a material which when heated at a requisite temperature would volatilize or release a volatile component. The following substances were tried:

NaF	500°C.	216 hrs.	fluoro-sodalite + albite
$Na_2Cr_2O_7$	500°	29	chrome-noselite + albite
Perlite (H_2O)	500°	29	no change
$Al_2O_3.xH_2O$	500°	166	no change
$Al_2O_3.xH_2O$	700°	75	nepheline + albite
I_2	500°	61	no change.

The pressure existing in the tubes was probably not more than a few atmospheres.

Synthetic glass was subjected to various hydrothermal conditions in the Tuttle quenching apparatus; the data obtained are presented in table 2 and plotted in figure 14. The solid line is the equilibrium curve between analcite and nepheline + albite + H_2O. The albite obtained in these runs gives a powder pattern similar to that of synthetic albite obtained in other systems. It differs, however, from the pattern obtained from some natural albites. The analcite produced gave a powder pattern similar to that found in the Hanawalt File (II-932) within

TABLE 2

Hydrothermal Treatment of Synthetic Glass of Jadeite Composition

Temperature °C.	Pressure p.s.i.	Time hrs.	Products (per cent present)
500	7500	1.5	Anal. (90)
525	7500	96	Anal. (50), Ne + Ab (50)
550	7500	96	Ne + Ab (80)
380	15000	40	Anal. (100)
510	15000	24	Anal. (100)
525	15000	24	Anal. (100)
550	15000	24	Ne + An (1)
{ 515	15000	16	Then T raised to 560
{ 560	15000	76	Anal. (75), Ne + Ab (25)
575	15000	1.2	Ne + Ab (10)
590	15000	18	Ne + Ab (90)
800	15000	69	Ne + Ab (50)
885	15000	6	Ne + Ab (rare)
900	15000	1	Ne + Ab (90)
950	15000	1	Ne + Ab (1)
985	15000	1	Ne + Ab (rare)
1025	15000	2.5	Glass
1040	15000	1	Glass
550	22500	24	Anal. (100)
550	30000	24	Anal. (100)
575	30000	24	Ne + Ab (1)
575	38000	0.5	Anal. (100)

the error of measurement. The dashed curve represents exploratory runs made to determine the equilibrium between nepheline + albite and liquid. No jadeite was encountered in any of the runs. It should be apparent that in the quenching apparatus only the fields nepheline—analcite—H_2O and albite—analcite—H_2O can be realized below the solid curve. It is conceivable that jadeite could form in the analcite range in an environment deficient in water with respect to analcite. The sealed capsule technique of Goranson could be used to investigate this region, however another method was tried but not explored fully. The method consisted of pressing a mixture of analcite and jadeite glass into a small, thick-walled, metal container under many tons pressure. This packing procedure was repeated until the container was completely filled. The container was then sealed with a silver washer and heated at 500°C. It was reasoned that the mixture would be deficient in water with respect to analcite, and therefore represent a point on the analcite—jadeite join. No change was observed in the mixture after five days' heating; no jadeite

was produced. Perhaps the use of other materials, smaller grain size, and longer heatings at various temperatures would prove fruitful.

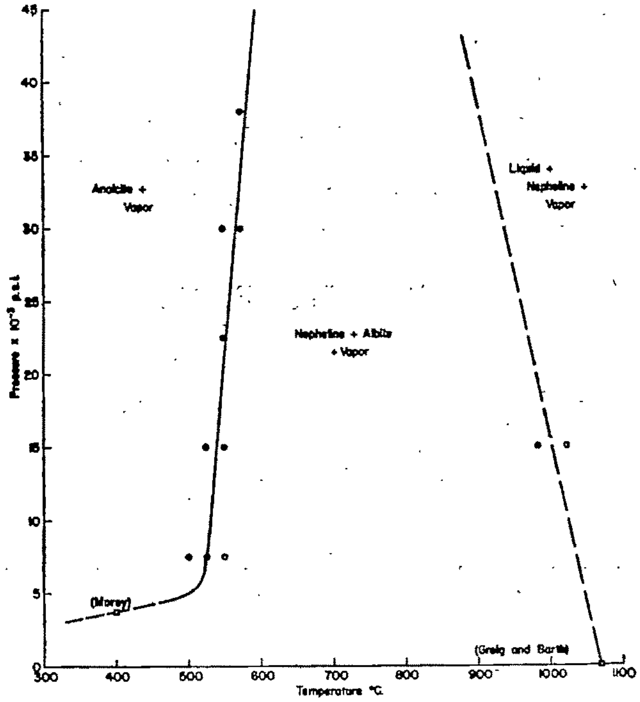

Fig. 14. Hydrothermal treatment of synthetic glass of the jadeite composition.

Several runs were also made with powders of the jadeite composition consisting of such materials as sodium disilicate, $Al_2O_3.xH_2O$ (approximately 8 per cent H_2O by weight), quartz, and crystallized sodium tetrasilicate glass. The products were the same as those obtained with synthetic glass.

Natural crystals of jadeite from Burma (USNM #94829) were also subjected to various hydrothermal conditions in the Tuttle apparatus. In general the results were the same as those for the synthetic glass. Below the solid curve the jadeite was completely altered to analcite; above the curve it was decomposed completely into nepheline and albite.

Thermodynamics. In anticipation of a direct experimental determination of the pressure and temperature conditions under

which jadeite is stable, an indirect thermodynamic approach can be made. The approach is essentially that of determining the thermodynamic properties of the phases in the assumed reaction: nepheline + albite = 2 jadeite. The P and T conditions under which this reaction may go can be computed from these properties. Whether the reaction will actually go or not, that is, if the rate is sufficient, cannot be determined at present.

It is of interest to outline the information necessary to make such a computation. The criterion that a reaction may go is that the free energy change be negative ($\Delta F < 0$). For the above reaction:

$$\Delta F = 2F_{Jd} - (F_{Ne} + F_{Ab}) < 0.$$

It is not convenient to compute the free energy of each phase directly, therefore the following relation is used:

$$d(\Delta F) = \left.\frac{\partial(\Delta F)}{\partial T}\right|_P dT + \left.\frac{\partial(\Delta F)}{\partial P}\right|_T dP \quad .$$

The coefficient of dT in the first term of the expansion is exactly equal to $-\Delta S$ (S = entropy) which may be evaluated from heat capacity data. The coefficient of dP in the second term of the expression is exactly equal to ΔV (V = volume). The volume at a specific temperature and pressure may be obtained by determining the terms of the expansion:

$$dV = \left.\frac{\partial V}{\partial T}\right|_P dT + \left.\frac{\partial V}{\partial P}\right|_T dP + \left.\frac{\partial^2 V}{\partial P^2}\right|_T dP^2 + \left.\frac{\partial^2 V}{\partial T^2}\right|_P dT^2 + \left.\frac{\partial^2 V}{\partial P \partial T}\right|_{T,P} dPdT$$

The first term is the thermal volume expansion and the second term is the compressibility. Since these two terms are essentially linear, the third and fourth terms are negligible. The last term is also considered to be negligible, but its value may be estimated with some accuracy if necessary.

In summary, it is necessary to have the following data for each phase of the assumed reaction before its free energy may be computed; entropy at 298°K., heat capacity constants, heat of formation at 298°K., compressibility, and thermal volume

expansion. Various laboratories are now determining these values.[1]

DISCUSSION

As stated at the outset, jadeite has been regarded as a "high-pressure mineral" mainly on the argument that it occupys a smaller volume than its chemical equivalents, nepheline + albite. In the preceding section it was recalled that the free energy of a reaction is a function of both volume *and* entropy. Therefore it is not sufficient to consider only the volumes of the phases. Furthermore the volume is a function of both temperature and pressure. In fact, the usually disregarded thermal expansion term is of greater magnitude than the compressibility term; the differentials in a reaction of several phases would be accordingly affected. It is, therefore, the opinion of the writer that to assume pressure as the sole agent which drives a hypothetical reaction is an unwarranted inference. If a reaction is known to be possible on other grounds, it will proceed under pressure in the direction of smaller volumes. However, the mere fact that the supposed products are of smaller volume than the reactants is not sufficient basis for inferring that the reaction will take place. These arguments do not preclude the possibility of jadeite being a high-pressure mineral.

The field occurrence of jadeite, as lenses and masses in a contact zone, suggest that it formed under special local conditions. The fact that it occurs in veinlets penetrating the wall rock might indicate conditions which are usually referred to as pegmatitic. One interpretation of the fragment of nepheline containing needles of jadeite is that the jadeite formed first under a set of conditions which changed to a range in which

[1] Dr. K. K. Kelley (personal communication, 1949) has obtained provisional values for the change of standard entropy at 25°C. for the following reactions:

(1) $2Jd \rightarrow Ab + Ne$

(2) $Jd + Qtz \rightarrow Ab.$

If the heat of reaction in (1) is greater than $\Delta H_{298.16} = 4380$ and in (2) is greater than $\Delta H_{298.16} = 2210$, then jadeite would be stable at room temperature. The magnitudes of these heats of reaction are not unreasonable, and, Kelley says, the "signs of the required heats of reaction are those that would be predicted in consideration of the high density of jadeite." The heats of formation are now being obtained by Kracek and Neuvonen at the Geophysical Laboratory.

nepheline and albite were stable before crystallization was complete. The analcite dikes containing crystals of sodic pyroxene have already been mentioned. Another interpretation is that in the assumed reaction $2Jd = Ne + Ab$, the combinations $Jd + Ne$ or $Jd + Ab$ are possible equilibrium associations. The local predominance of associated minerals and mineral combinations might be claimed as either due to inhomogeneity or to non-equilibrium. The Burmese and Japanese occurrences of jadeite might be analogous to the occurrence of anthophyllite as a contact mineral around serpentine bodies. Anthophyllite has been shown by Bowen and Tuttle (1949) to be metastable under laboratory conditions but may have been rendered stable in nature by the addition of other constituents. In this connection, the common occurrence of acmitic pyroxenes has already been mentioned.

The structural analysis leads to the conclusion that jadeite is a pyroxene with the type structure of diopside. It also suggested that the field of stability of jadeite probably lies in a region of low temperature. Further, it may be dependent on high pressure or may be hydrous. The stability of the jadeite structure is not believed to be dependent on "structural wedging" by some "impurity" but may owe its existence to the presence of iron, hydroxyl, or an excess of aluminum.

The inability to synthesize jadeite at atmospheric pressure has been an argument in favor of the necessity of pressure. However, not all the standard methods of crystal synthesis have been exhausted nor is the field closed to new technique. Jadeite is, of course, not the only pyroxene which has not been synthesized. The lithium analogue of jadeite, α-spodumene (monoclinic), has not been produced with certainty in the system eucryptite—silica, although a substance having similar properties has been synthesized (Roy, Roy, and Osborn, 1949). On the other hand β-spodumene (hexagonal) is readily obtained. Oddly enough, α-spodumene occupies 28 per cent less volume than its chemical equivalents eucryptite + quartz. It can be said that jadeite has not been produced from synthetic or natural materials in the presence of catalysts, under moderate pressures, or in related systems.

The experiments completed do limit the possible range of stability of jadeite. A consideration of the metastable melting

of natural jadeite gives rise to the following picture. Assume that the material X lowered the melting point of the nepheline-albite mixtures such that a field of jadeite appeared (fig. 15).

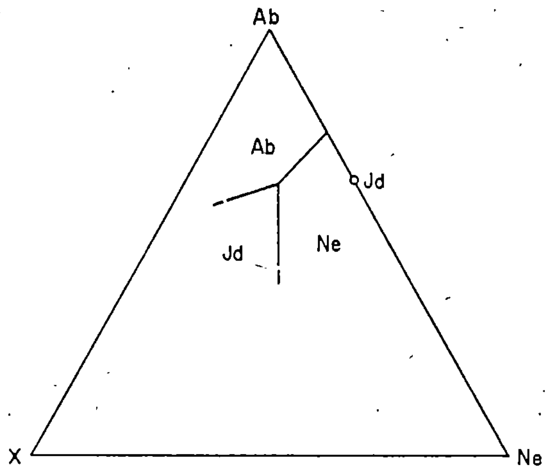

Fig. 15. Hypothetical field of jadeite in the system, X — Nepheline — Albite (after Bowen).

The projection of this surface (fig. 16), representing the liquidus of the jadeite field, would intersect the nepheline-albite binary at the metastable point of jadeite. One possible inter-

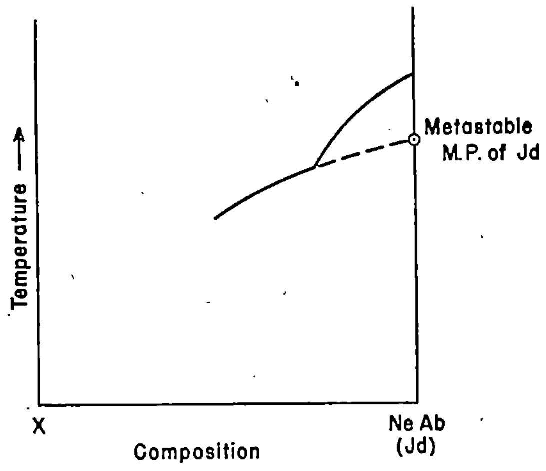

Fig. 16. Hypothetical pseudobinary, X — Jadeite (after Bowen).

pretation would be as in figure 17. Considered as a function of

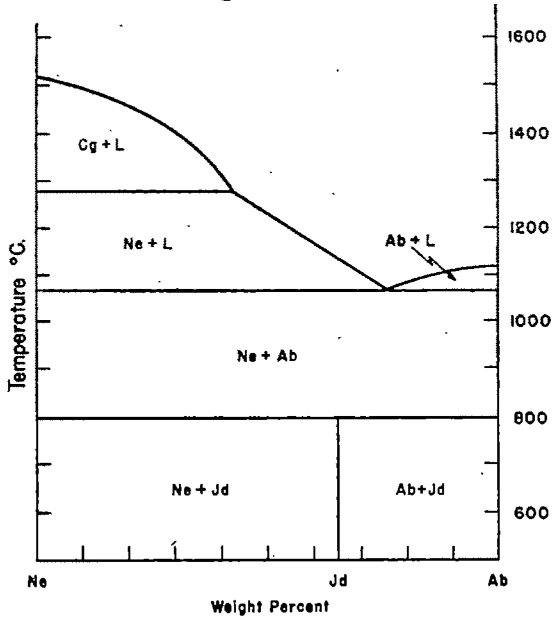

Fig. 17. Hypothetical binary system, $NaAlSiO_4 - NaAlSi_3O_8$ (modified and simplified from Greig and Barth, 1938).

pressure the picture becomes that of figure 18.

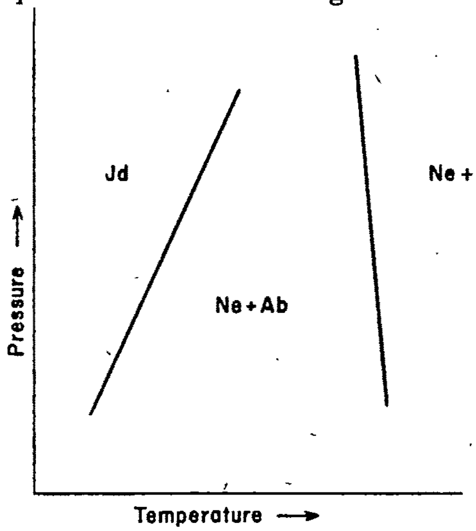

Fig. 18. Hypothetical stability relations for the jadeite composition as based on figure 17.

Using the principles of Schreinemakers (1916) and others, the metastable melting may be explained in another fashion. Consider the P-T relations of the four phases Ne, Ab, Jd, and Liquid. The sequence of curves about an invariant point can be shown to be as in figure 19. A two-component system was

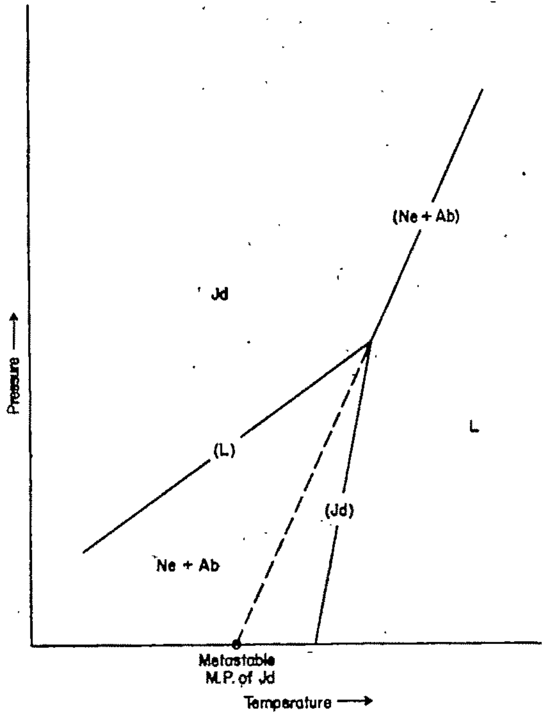

Fig. 19. Theoretical P-T relations in the system, Nepheline — Albite.

assumed; only the associations of the jadeite composition are represented, and the composition of the liquid was taken to be the same as jadeite. If curve (L) intersects the ordinate axis, jadeite is indeed a pressure mineral. The metastable reaction Jd = L as drawn might possibly be realized at atmospheric pressure.

When all possible compositions are considered, it is seen that the association Jd + Ne + Ab is theoretically impossible in any system except at the decomposition temperature of jadeite as represented in figure 17. The fact that Bauer (1896) found such an association could have several explanations. It could be argued that the presence of another component,

for example CaO in the feldspar, would permit a three-phase equilibrium. It is possible that the jadeite was formed exactly at the triple point. Still another reason might be that equilibrium was not obtained; that the reaction did not go to completion. On the other hand, it might suggest that the reaction Ne + Ab = Jd is not a valid assumption for the formation of jadeite.

Perhaps the most fruitful approach to the jadeite problem is in the system Anal—Ne—Ab. Considerable use could be made of apparatus which would permit the regulation of water present at a wide range of P and T. There is the possibility that jadeite requires either H_2O or OH in its structure, but there is little doubt that an "anhydrous" jadeite exists.

In conclusion, the writer believes that the field of stability of jadeite probably lies below 800°C. and that volatiles are necessary to promote its formation.

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SPECIES CRITERIA IN OSTEOSTRACI, WITH SPECIAL REFERENCE TO THE GENUS TREMATASPIS

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ABSTRACT. An attempt is made to compare species criteria as used in the Genus *Tremataspis* with those used in establishing species in the other genera of the order *Osteostraci.* Exception is taken to Denison's use of histologic characters of the shield as an adequate basis for placing specimens which differ in other respects in the same species.

ONE of the problems which arises to plague every practicing taxonomist is that of establishing valid criteria for the delimiting of species. Few of us would admit serious doubt as to the validity of the species concept, but certainly the criteria we use in our attempt to establish the identity of the species are rather arbitrary. There is an old statement somewhere to the effect that "God made the species, man the higher categories," but if that were true it would have helped mightily if the species had been more carefully labelled. The criteria we use in setting up our taxonomic categories may not be "man-made" but they are definitely "man-selected."

One of the most realistic definitions of species which I happen to have seen is that of Tate Regan (1925), which can be paraphrased to state that a species is any group which has been so designated by a "competent taxonomist." Huxley (1942), in commenting on that definition points out that the definition of competent needs some clarification. Perhaps it would be better stated that a species is any group which has been so designated by a competent taxonomist who has worked with the group under discussion.

We find, to be sure, that there are disputes among the "competent taxonomists" working in the same group as to what shall be valid criteria, but it would seem as though such questions could be settled by following principles which the workers on that group could agree upon. Whether it will ever be possible to establish certain "grades of organization" which can be applied to species criteria throughout the animal kingdom, or even through entire classes or phyla, is questionable, although closer agreement than present schemes indicate would certainly be desirable. Probably no biologist would deny that

the number of species of insects is justifiably enormous, but there would be found, I believe, a considerable number of us who would question whether the concept has exactly the same significance that it has in mammalogy.

Even within the class Mammalia the number of species recognized increases markedly as one goes from the large to the small forms. There are many more species of rodents recognized than there are of carnivores. It may be another valid question whether a "species" among rodents is the morphological equivalent of a "species" among carnivores, *i.e.* whether they recognize similar "grades of organization."

When, as in the present paper, we deal with fossil forms there are still other problems which bedevil the would-be systematizer of the systematists. On the strictly morphological level to which we are almost invariably limited in dealing with fossil forms it has been pointed out that the type of criteria used in specific distinctions when dealing with living forms are frequently unavailable when we deal with fossils. In discussing with another taxonomist the problem of separating species in the *Tremataspidae*, during the period when I had my 1938 paper on that group under preparation, he remarked that he believed one was justified, in dealing with fossils, in recognizing as distinct species any form which could be consistently recognized by the investigator. In his account of the history of land mammals, Scott (1937) wrote that he believed that what we recognize as species in fossil mammals would be more nearly equivalent to the genera of the neo-taxonomist. I would not advocate adopting that procedure. It would result in an enormous amount of confusion to do so.

Another difficulty faces the paleo-taxonomist when he attempts to correlate his work with that of the neo-taxonomist. Population genetics seems to be entering the thinking of the taxonomists, and rightly. Simpson (1943) has stressed the concept that among modern forms a species is a breeding population. How far can we go in the recognition of such populations among fossils? How great a stratigraphic range should be regarded as justifiably included in the same breeding group?

In his scholarly discussion of "Tempo and Mode in Evolution" Simpson (1944) has made an interesting attempt to bring genetics and paleontology somewhat closer together. It has

occasionally been possible to recognize in fossil series what are apparently the effects of single mutations. Simpson has discussed the case of digit reduction in the horse series from that view-point and seems to have made out a good case for it. But even in neo-biology we are still far from reaching any agreement as to what degree of genetic change constitutes specific distinction. It would be very convenient if we could erect a scheme based on mutations, such that so many mutations constituted sub-specific distinction, a certain additional number differentiating species, etc.

Growth stages bring in still another problem for the paleontologist. Bashford Dean (1899) once discussed the suggestion that *Paleospondylus* might be a larval "lamprey." Among some incomplete notes left by Dr. Wm. Patten were some sketches in which he appeared to be trying to correlate the structure of the same creature with known larval forms, probably Tunicate. In 1947 Denison suggested that one species of *Tremataspis* which I had separated, *T. patteni* (Robertson, 1938), was based on what probably were juvenile specimens of *T. mammillata.* Our inability to follow through the development of these creatures leaves uncertainty as to how far we can go in identifying growth stages.

In 1945 I published a discussion of cephalaspid genera and species. The present paper is an extension of this discussion to include other *Osteostraci.* It is an attempt to see whether it is possible to set up a standard set of criteria for family, genus, and species within the entire order. It has seemed to me that the *Osteostraci* would lend themselves well to such an attempt, in that there is a rather close adherence to pattern within the order, with an apparent similarity of habitat throughout.

The more immediate stimulus to make the attempt comes from the above-mentioned paper by Denison (1947), in which he suggested certain revisions of the species of *Tremataspis.* It has seemed to me that it should devolve upon me either to acknowledge his strictures on these species as justifiable or to show to what degree I regard his criticisms as unsound. The question in this case should be settled only after analysis of the broader question of species criteria in the *Osteostraci.*

In my discussion of cephalaspid genera and species (1945) I

laid emphasis on one aim of taxonomy. When we classify any group of objects we are attempting to bring order into the grouping so that when any of the terms of reference are used they will have definiteness of meaning. In other words, one of the major aims of taxonomy is specificity of reference. It is sometimes necessary to revise a classification, but it does not appear to be justifiable to change it because of slight differences in viewpoint, or on the basis of some theoretical construction which represents simply another hypothesis. In general, according to my philosophy of taxonomy, uniformity among workers with a particular group is at least a major consideration and should not be sacrificed without a very thorough consideration of the viewpoints of all workers concerned.

My present view regarding the origin of species is simply that, generally under conditions of isolation, geographic, ecologic, etc., mutations have accumulated in groups previously conspecific to such an extent that students of the group would recognize them as specifically different. In some cases environmental selection has played a definite role in the separation, especially when one group, either the parent or an off-shoot, has become extinct, and in every case selection plays a part in the ensemble of characters which constitute the distinct species, since the organisms constituting the species had to be "going concerns" in their environment, but even when selection did not influence the distinction between the species isolation would tend to result in differentiation.

There are recognized at present the following families of *Osteostraci*: *Cephalaspidae*, *Trematapsidae*, *Dartmuthiidae*, and *Oeselaspidae*. In my 1945 paper, I suggested that ***Didymaspis*** should perhaps be raised to family rank, adding thus a fifth family, the ***Didymaspidae***. ***Didymaspis*** has been variously placed. Recent workers have generally listed it under the *Cephalaspidae*. Romer listed it under the *Dartmuthiidae* (1945, p. 572).

Comparison of the papers of recent workers in the taxonomy of the cephalaspids indicates that these workers in general have used the following list of criteria of species:

(1) Shape and proportions of the shield;
(2) Configuration of the rostral margin of the shield;

(3) Shape, direction, and ornamentation of the cornua of the shield;
(4) Shape and size of the "pectoral sinuses";
(5) Shape and extent of the "interzonal" region of the shield;
(6) Size and shape of the orbital openings;
(7) Shape and extension of the lateral and dorsal fields;
(8) Ornamentation.

Comparison of the criteria used in establishing species of *Tremataspis* gives the present author some qualms, since only one species recognized as valid in my 1938 paper had been based on material other than that of the Patten Collection at Dartmouth College. Patten had erected but very inadequately characterized two species, *T. milleri* and *T. mammillata* (1931), so that, in addition to naming and describing four new species, my paper was the first actual description of the two erected by Patten. Thus the problem facing me here is the discussion of the criteria I used at that time and the attempt to correlate this with the criteria recognized in the above list for the cephalaspids.

Unfortunately only one species has been recognized in the genus *Oeselaspis* and only one in the genus *Dartmuthia*. The same is true of the genera *Saaremaaspis* and *Rotsiküllaspis*. Two species of *Witaaspis* were recognized (Robertson, 1945). They were distinguished on the basis of ornamentation, including the form of the median dorsal crista.

The specific criteria used for the species of *Tremataspis* were as follows:

(1) Form and proportions of the shield;
(2) Form of the naso-hypophysial fossa and relation of the aperture to the fossa;
(3) Form of the median dorsal crista of the shield;
(4) Ornamentation of the shield;
(5) Microscopic appearance of the superficial layer of the shield, especially the distribution of the fine "pores."

There are certain fundamental differences in shield plan in the *Trematraspidae* from that in the *Cephalaspidae* which make some of the cephalaspid criteria unusable for tremataspids. The rostral margins of the shields are similar throughout in the tremataspids. Cornua, pectoral sinuses, and interzonal region are absent in tremataspids, correlated with the greater

extent posteriorly of the shield. Dorsal and lateral fields are in general very uniform, although in *T. patteni* the form of the anterior lateral field differs from that found in any of the other species.

The criterion of specific distinction I used was difference in one or more of these characteristics. Conversely, identity of species was based on similarity in all the diagnostic features.

On the basis of shield proportions the seven species could be divided into two groups, one including *T. schmidti*, *T. rohoni*, *T. scalaris*, and *T. panderi*, the other including *T. milleri*, *T. mammillata*, and *T. patteni*, although the distinctly larger size of *T. milleri* might be used as a basis for placing it in a separate group.

On the basis of form of the naso-hypophysial fossa and aperture *T. schmidti*, *T. milleri*, *T. rohoni*, and *T. patteni* fall into one group, *T. mammillata* into another. This feature is not adequately preserved on the specimens of the other species.

The form of the crista appears to be different on each of the seven species, although the preservation of that region on the specimen of *T. scalaris* is not good.

On the basis of the ornamentation of the shield, chiefly the pattern of tubercle distribution, *T. milleri* resembles *T. schmidti*, although there are fairly definite differences. *T. patteni* and *T. mammillata* are similar in this, with the exception of the thinness of the *T. patteni* shield, which was one of the major reasons for Denison's decision (1947) that it might be a juvenile stage of the other species. *T. scalaris* and *T. panderi* resemble *T. mammillata* in tubercle distribution, but each has a peculiar, "ladder-like" marking on the dorsal shield surface which I used as the differentiating criterion.

The microscopic appearance of the shield surface, especially the distribution of the fine "pores," was a final character used. On this basis *T. schmidti*, *T. milleri*, and *T. rohoni* were definitely distinguishable as separate forms. *T. patteni*, *T. scalaris*, and *T. panderi* resembled *T. mammillata*.

In 1947 Denison stated that *T. patteni* was based on immature specimens of *T. mammillata*, and that *T. scalaris* and *T. panderi* were based on specimens of *T. mammillata* showing growth anomalies which accounted for the "ladder-like" orna-

mentation. His major criterion for conspecificity was the microscopic (histologic) structure of the bony shield, *i.e.* the last character I listed above.

I am willing to concede that Denison's contention might be correct, that *T. patteni* may be based on immature specimens, the shield characters which superficially seem to distinguish it from other species being due to immaturity. However, until additional specimens definitely establish the validity of his contention I believe it wiser to retain the species. There were only a few specimens of this type in the collection. Moreover on the basis of the other characters listed above there is doubt as to its identity with *T. mammillata*. It resembles this species in pore distribution, distribution of the dorsal tubercles, and shield proportions; differing from it in the form of the nasal fossa, in which it is more like *T. schmidti*, in the form of the dorsal crista, and in the emargination of the anterior lateral field. In a foot-note (1947, p. 358) Denison discounted these differences on the basis of the thinness and poor preservation of the shields.

The crucial point on this question is whether identity in histologic structure of the bony exoskeleton is a valid criterion of conspecificity. In his paper Denison states (p. 337): "It was found that the microstructure of the exoskeleton, viewed either superficially under xylol or in thin sections, offered clear characters which sufficed for a *specific identification* of even a small fragment of *T. mammillata*, *T. milleri*, *T. schmidti*, and *T. rohoni*. The other species described by Robertson were shown to belong to *T. mammillata*." It is on the basis of this microstructure of the bone and the extreme thinnness of the exoskeleton of the specimens referred to *T. patteni* that Denison regarded them as being simply juvenile specimens of *T. mammillata*.

Denison's hypothesis, that "the exoskeleton was formed only after the attainment of full growth" (p. 362) and that these specimens of *T. patteni* offer conclusive proof of the hypothesis, is attractive, since many of us who have worked with the ostracoderms have been puzzled over growth methods. It is important, however, to be more certain of this before the conclusion can be accepted.

My use of the microstructure of the shield as a taxonomic

character (1938) perhaps needs explanation if I am to contend that Denison's union of species on its basis is not justified. I have never regarded histological characters as adequate basis for specific *identification.* Rather it was a character in which there were definite differences in pattern, and I used it as an additional criterion for *separation* of species. If histology of the bone were to be used as a basis for union of vertebrates at the specific level I suspect that we would very markedly reduce the number of species. Certainly I would regard it as a totally different grade of organization than the characters listed earlier for cephalaspids.

The case against the other species, *T. scalaris* and *T. panderi,* is somewhat different, although here again Denison has used the microstructure of the shield as the basis for uniting them with *T. mammillata.* When I first found the specimens which I later separated as *T. scalaris* and *T. panderi* I considered the question of anomalous characters. My reason for rejecting that explanation of the ladder-like markings was the symmetry of these markings. They may be related to the pores and polygonally-arranged canals ("sensory canals" of Denison), but that in itself does not indicate that the difference from the usual pattern is simply due to "growth deficiency in these specimens." It is not demonstrated that these peculiar markings might not have been permanent markings of a variant form rather than anomalous characters of *T. mammillata.* Had they shown less symmetry of pattern; had they been unilateral or irregularly-arranged markings on the shield, I would not regard them as taxonomically significant.

Denison's contentions regarding these three species may be correct, but it still appears to me to be wiser to retain the independence of distinguishable forms until we can be somewhat more certain that they represent either juvenile specimens or anomalous specimens of another species.

I wish here to express a doubt regarding the conclusion that the system of "mucous canals" in the skeleton of *Tremataspis* was a part of the "sensory canal system." Denison's careful work on the exoskeletal structure (1947) seemed to indicate that the grooves of the lateral line system followed lines of these canals and apparently had openings into them. That does not necessarily mean that they were parts of a functional

whole. I puzzled a good bit over the pathway of innervation of the lateral line canals in *Trematаspis* and had come to the conclusion (1938, pp. 199-200) that the pathway through the exoskeleton must be by way of these pore canals, but I know of no morphological or physiological reason why the fine nerve branches might not make their way via these canals at the same time that the canals performed additional functions of their own, such as, perhaps, mucous secretion. I stated (p. 199) regarding the relation of the sensory canal grooves to the exoskeleton that there were "at least occasional apertures in the bottoms of grooves. These apertures prove, on dissection, to connect with the system of channels which pervades the bony shield in the same way as do the pores so abundant over the general surface." I then quoted from Stensiö (1927) that he had found on *Tremataspis* "branches from the vascular system opening into the mucous canals on the basal side, a state of things which shows that the mucous canals received vessels and nerves through the vascular canal system," and then commented: "Possibly this is the solution of the innervation difficulty. At least for the present no other appears available."

My major reason for doubting the sensory character of this intricate network is perhaps teleological. Denison states (1947, pp. 350-52): "It thus appears that the Silurian *Tremataspis* had its body entirely covered, even on the scale-covered tail, with a network of canals whose function was to receive vibratory stimuli. Such a generalized system of surface receptors may have been the primitive arrangement in *Osteostraci*, and indeed in vertebrates. We can see in *Tremataspis* the beginnings of specialization of parts of the canal system into what is known as the lateral line system of later fishes. This involves the assumption of a linear arrangement of the canals in certain regions, the acquisition of a more open connection with the exterior, and presumably the enlargement and specialization of the nerve branches which supply the definitive lateral line canals."

To me it does not make sense. I realize that the teleological argument is frowned upon by biologists, but I cannot resist in this case asking why a semi-benthonic, weak-swimming creature like *Tremataspis* should have been so extravagantly blessed with receptors. The canals in question may have served to

secrete mucus or may have been used for some other function, but the fact that they indicate possible pathways for the nerve fibres whose endings innervated the sensory canals of the lateralis system does not seem to me to justify the assumption that they themselves constituted "sensory canals."

In summary, it would appear possible in the *Osteostraci*, in so far as those groups are concerned which contain more than single species, to use specific criteria of what seem to be comparable "grades of organization," although the detailed characters on which specific distinctness is based in one genus cannot be carried over to all other genera within the order, and sometimes cannot be used for different genera within the same family. This was to be expected on the basis of what we know of taxonomic work in general and what we believe to be the nature of the evolutionary processes by which species arise.

The class *Ostracodermi* differs sufficiently from other vertebrates that it seems justifiable to place it in a super-class, *Agnatha* (Robertson, 1942, pp. 147-149), characterized by lack of true vertebrate jaws and by gill pouches of the cyclostome type, characters which have led to the union of the modern cyclostomes with the fossil ostracoderms.

The class has been subdivided into two sub-classes, *Pteraspidomorphi* and *Cephalaspidomorphi*, on the basis of type of exoskeletal pattern and apparent differences in the relation of the individual branchial apertures to one another, the order *Osteostraci* constituting the best-known group of the cephalaspidomorphs, differentiated from the other order or orders, dependent on the detailed classification adopted, by the type of shield structure.

Familial characters of this order (Robertson, 1945, p. 186) include form and extent of the shield, presence or absence of cornua and the associated pectoral sinuses, number of lateral fields, extent of dorsal field, and size and number of oralobranchial plates.

Sub-families have been recognized only in the *Cephalaspidae* and are based on characters to some extent intermediate between those used for family differentiation and those characterizing genera, namely, the extent of the cornua and pectoral sinuses, size of the dorsal and lateral fields, and, in

Stensiö's differentiations (1927), differences in distribution of nerves to the lateral fields.

Generic distinctions are of importance chiefly in the cephalaspids, since the other families, with the exception of the *Dartmuthiidae*, are as yet based on single genera. *Rotsiküllaspis* (Robertson, 1938, pp. 490-493; 1945, p. 190) has been placed in the *Dartmuthiidae*, the generic differences being conformation of the posterior margin of the shield, type of ornamentation, extent of the lateral fields, and form and arrangement of the oralo-branchial plates. Romer (1945, p, 572) concurs in this placement of *Rotsiküllaspis*, but also lists *Didymaspis* in this family, as mentioned earlier in this paper. I am inclined, however, toward disposition of this genus (1945, p. 789) as a separate family. The possession of rudimentary pectoral sinuses, the peculiar form of the lateral fields, and the general resemblance in form to *Oeselaspis* are the major reasons for this decision.

The series of distinctions listed for genera within the *Dartmuthiidae* does not differ materially in what I have termed "grade of organization" from those used for cephalaspid genera, namely, general form of the cornua and pectoral sinuses, extent of the dorsal and lateral fields, extent of the shield, and relation of the dorsal shield to the ventral armor.

Specific criteria have been discussed earlier in this paper.

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NOTE ON SURVIVAL OF FABRIC CHARACTERS IN YULE MARBLE AFTER HEATING TO 700° C.*

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(with comments by Joseph L. Rosenholtz and Dudley T. Smith)

IN 1948 J. L. Rosenholtz and D. T. Smith of Rensselaer Polytechnic Institute determined linear thermal expansion of the marble from Yule quarry, Colorado, that has been the subject of high-pressure deformation experiments by D. Griggs and of detailed petrofabric analysis by E. B. Knopf and F. J. Turner. (For an account of this work and a full statement of the properties of Yule marble, see Knopf, 1949.) The thermal expansion tests were carried out on three oriented, mutually perpendicular rods, cut from the same block as was used for detailed petrofabric analysis by Turner (1949). These rods may be referred to as the P, Q and R rods, respectively normal to the faces P, Q and R of the parent block. [P rod is elongated N-S, horizontal, parallel to foliation; Q is E-W, horizontal, normal to foliation; R is vertical, parallel to foliation.]

The maximum coefficient of thermal expansion, that measured in rod Q, was found to be greatly in excess of that for a single crystal of calcite. Moreover, notable permanent expansion of all three rods was recorded at the end of a single cycle of heating to 700° C. and subsequent cooling to room temperature. A further heating-cooling cycle showed no such effect, however, the expansion on heating being followed by equivalent contraction on cooling through the same interval of temperature. It would seem that in the first cycle of heating some internal structural adjustment occurs, which results in permanent relief of a strain present in the untreated marble. With a view to determining to what extent such relief of strain might be reflected in the fabric, the writers carried out a detailed petrofabric analysis on a longitudinal section cut from the thermally expanded rod Q, and oriented parallel to plane R, using the same technique as had previously been employed in investigating the fabric of the untreated rock (Turner, 1949).

* This paper embodies results of research sponsored by the Institute of Geophysics, University of California.

The fabric data were compared carefully and scanned for possible evidence of recrystallization, change in preferred orientation of calcite grains, and change in orientation, number or closeness of spacing of glide lamellae. In every respect the two fabrics were found to be almost identical. This conclusion is unexpected enough to warrant recording the essential data.

Yule marble is an even-grained rock. But sections of the untreated marble show a small percentage (by area) of notably small grains whose diameter is one-third to one-fifth that of the predominant type of grain. In the single section of expanded marble, small grains are less numerous; but the degree of dissimilarity is of the same order as the variation observed between different parts of one large section of untreated marble. There is thus at most only a very inconclusive indication that some of the smaller grains may have been eliminated by recrystallization during the heating test. The writers would disregard this evidence completely.

Figures 1, 2 and 3 are orientation diagrams prepared from optical and crystallographic measurements made on 100 typical calcite grains in the thermally expanded marble. They show the preferred orientation pattern for *c* axes (fig. 1), observed $\{01\bar{1}2\}$ lamellae (fig. 2), and edges $[e:e']$ between observed $\{01\bar{1}2\}$ lamellae in individual grains.[1] These may be compared

[1] More than half the measured grains show two sets of $\{01\bar{1}2\}$ lamellae only. In grains where three sets are present, one is almost always much weaker than the others; this weak set was omitted when plotting edges of the $[e:e']$ type—just as was done in the previous investigation.

Figures 1-4. Preferred orientation of calcite in Yule marble after heating to 700° C., based on measurements on 100 grains in a section (cut parallel to plane R). Inset figure gives geographic orientation of diagrams (lower hemisphere of projection, looking vertically downward).

Fig. 1. 100 *c*-axes, [0001]. Contours at 6%, 4%, 2%, 1%, per 1% area; maximum concentration 10%.

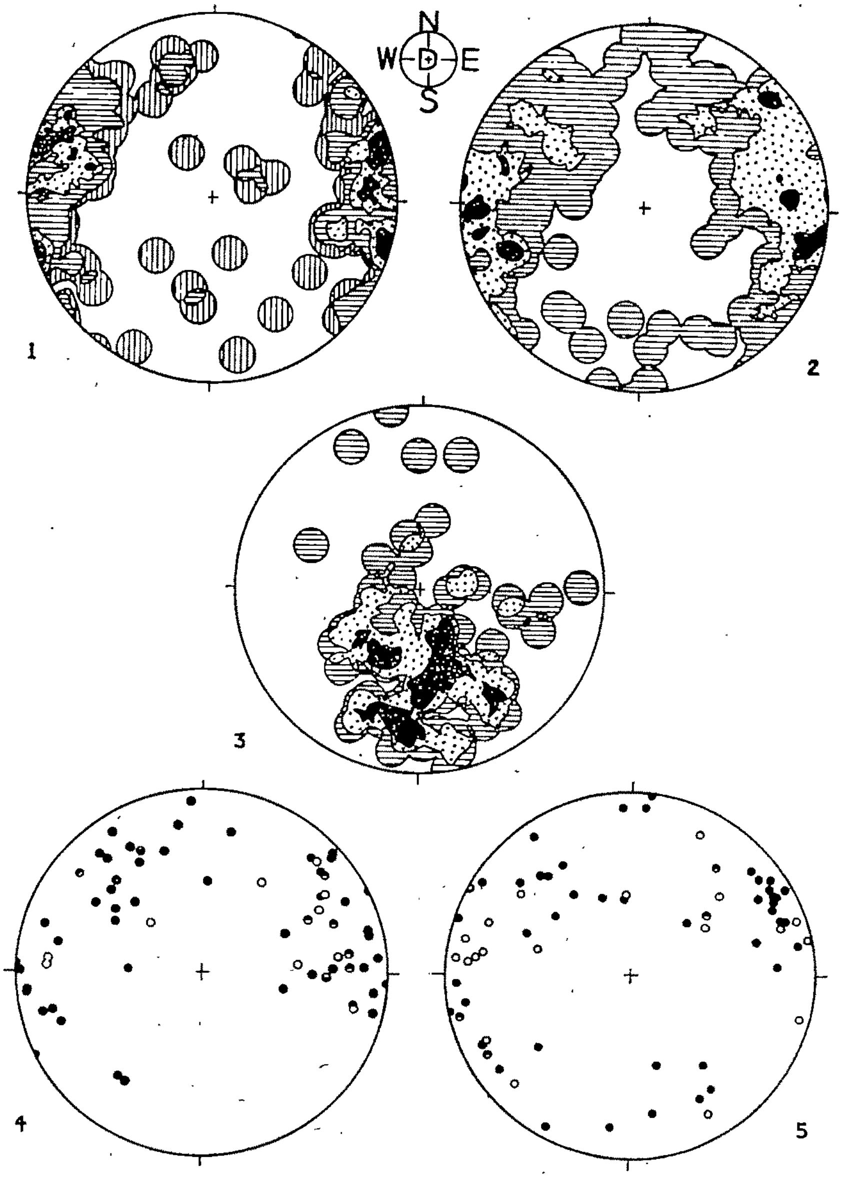
Fig. 2. 191 poles of $\{01\bar{1}2\}$ lamellae. Contours at 4%, 2%, 0.5%, per 1% area; maximum concentration, 5%.

Fig. 3. 82 edges $[e:e']$ between faces of $\{01\bar{1}2\}$. Contours at 5%, 3%, 1.1% per 1% area; maximum concentration, 7%.

Fig. 4. Poles of $\{01\bar{1}2\}$ lamellae recognizably twinned (solid circles); poles of $\{01\bar{1}2\}$ lamellae with spacing index $>$ 20 (open circles).

Figure 5. Yule marble, *untreated*, section cut parallel to plane R. Poles of $\{01\bar{1}2\}$ lamellae recognizably twinned (solid circles); poles of $\{01\bar{1}2\}$ lamellae with spacing index $>$ 20 (open circles).

with figures 8, 12 and 28 respectively in the previous paper (Turner, 1949, pp. 603, 605, 611). Corresponding diagrams for treated and untreated marble are so closely similar that the fabrics must be regarded as identical. This similarity applies also



to diagrams constructed for other crystallographic directions such as edges between $\{10\bar{1}1\}$ and $\{01\bar{1}2\}$. The preferred orientation patterns of the crystal lattices of calcite—as illustrated by the optic axes (fig. 1) and the visible deformation lamellae (figs. 2, 3)— have survived heating and cooling through two complete cycles without the smallest recognizable modification.

It was thought possible that the nature or closeness of spacing of deformation lamellae might have been changed to some extent by heating. To test this, counts were made of the number of sets of lamellae in which twinning could be recognized definitely (in one lamella or more) by symmetrical extinction when viewed parallel to the plane of the lamella between crossed Nicols. The number of continuous lamellae in each set, the number of these recognizably due to twinning, and the maximum width of the grain normal to the plane of the lamellae in question were also measured.

Similar counts and measurements were made for 100 grains (excluding small interstitial granules) in the corresponding section of untreated marble. The results obtained are as follows:

(1) The number of sets of $\{01\bar{1}2\}$ lamellae observed per 100 grains in untreated marble is 194; and of these 47 (24%) show one or more recognizably twinned lamellae. Corresponding figures for thermally expanded marble are 182 sets, 52 (= 28%) with recognizably twinned lamellae.

(2) In the untreated marble 13 sets of lamellae include one or more broad twinned bands; none such appears in the thermally expanded rock.

(3) The total number of individual $\{01\bar{1}2\}$ lamellae observed in all sets in the untreated marble is 912, of which 107 (12%) are definitely twinned. Corresponding figures for thermally expanded marble are 735 lamellae; 79 (11%) definitely twinned.

The greater total number of lamellae observed in the untreated rock noted under (3) above is partly due to the somewhat larger size of the grains measured in that section. A more satisfactory index of the closeness of spacing of lamellae in any set is given by the expression

$$\frac{\text{number of lamellae in the set}}{\text{width of grain normal to plane of lamellae}}$$

This we have termed the spacing index. The mean spacing index for all sets of well-defined lamellae was found to be 11.1 (per mm.) in the untreated rock as against 10.0 in the expanded rock. These indices may be corrected to include a value of 0 for every $\{01\bar{1}2\}$ plane not represented by observable lamellae; these corrected values are 7.0 (untreated) and 6.7 (expanded). Statistically identical closeness of spacing of lamellae brought out by these indices may be contrasted with the much higher values of mean spacing indices computed for lamellae in 100 grains measured in Yule marble elongated 4% in tension at room temperature and confining pressure of 2830 atmospheres[2]: these are 45.9 and 42.2 respectively.

Figures 4 (thermally expanded marble) and 5 (untreated marble) give plots of poles of lamellae having spacing index of 20 or higher (open circles), and of lamellae that are definitely twinned (solid circles). The lamellae with high spacing index are evenly distributed in the lamella girdle of the untreated marble; but in the expanded marble they are restricted to a more limited sector—the area of maximum lamella concentration in the top right quadrant. On the other hand heating seems to have had no significant effect upon the distribution of those sets of lamellae which include recognizable twins.

Results of the investigation may be summed up as follows:

(1) Yule marble heated to 700°C. and cooled to room temperature has maintained its fabric characters in great detail. There is no recognizable significant change as regards mean grain size, orientation of space lattice of grains, orientation of observed $\{01\bar{1}2\}$ lamellae, orientation of definitely twinned lamellae, spacing of lamellae per unit width of grain, or percentage of lamellae recognizably due to twinning.

(2) In two minor details the fabric data indicate that thermal expansion of Yule marble may possibly have been accompanied by very slight recrystallization at loci of

[2] We gratefully acknowledge use of this section—supplied by Professor D. Griggs, Institute of Geophysics, University of California, from material now in progress of investigation.

maximum strain. Broad twin lamellae, appearing in 7% of the observed sets of lamellae in the unheated rock are absent in the heated specimen. They may have been eliminated or reduced to linear dimensions by heating. Although the mean lamella spacing index is virtually identical in the two specimens, it is found that whereas 16% of the sets of lamellae have an index of 20 or more in the unheated specimen; this value is reduced to 10% after heating; moreover the orientation of such sets with high index is much more restricted in the heated rock. It is possible that neither of these minor apparent modifications of fabric is real.

The writers are greatly indebted to Professors Rosenholtz and Smith for the material on which this paper is based and for permission to discuss certain of their as yet unpublished data on thermal expansion of Yule marble. The detailed fabric analysis of heated and unheated Yule marble is part of a series of investigations made possible by a research grant from the Institute of Geophysics of the University of California. This is gratefully acknowledged.

For References, see p. 354.

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COMMENTS ON THE CHARACTERISTICS OF HEAT-TREATED YULE MARBLE

JOSEPH L. ROSENHOLTZ and DUDLEY T. SMITH

Studies which have been completed and others which are now in progress make it remarkably clear that fabric analysis and linear thermal expansion data may lead to the same conclusions concerning important aspects of the deformational history of rocks. The authors appreciate the invitation of Professor Turner and Miss Ch'ih to add their suggestions and comments here.

The coefficients of linear thermal expansion, α, of a deformed rock are not merely general handbook values; their analysis,

particularly when supplemented by fabric analysis, may be most revealing. In a comparison of the expansion of Yule marble with that of a single calcite crystal (Rosenholtz and Smith, 1949), it was found that structural changes are produced in the marble by heating to 700°C., as evidenced by the changes in α and, more particularly, by large permanent length recovery. Other studies on metals, which have not yet been completed, give conclusive evidence that compressive stresses above the yield point produce very large changes in α, as subsequently measured in the direction of compression. The equivalent of this condition was found in the Q rod of Yule marble, which is normal to the foliation and has an E-W horizontal geographic orientation.

Knopf (1949) and Turner (1949) have shown that approximately half of all grains examined in their fabric studies on Yule marble have their optic axes alined close to the E-W direction. Inasmuch as $\alpha\|$ for calcite is large and $\alpha\perp$ is both small and negative, a means is at hand for determining preferred orientation from expansion analysis. If it is assumed that all grains in Yule marble have their optic axes either parallel or normal to the E-W orientation, a *c* axis concentration of 39 to 49 percent parallel to E-W may be computed from the expansion data, depending upon the temperature range selected for computation. Turner found that 52% of 340 plotted *c* axes in untreated marble made angles varying from 55° to 90° with the plane of foliation. Since the heat-treated marble revealed no significant change in this respect, we may use either the treated or untreated marble for a grain by grain summation of $\alpha\|$ and $\alpha\perp$ computed from the individual *c* axis orientations. It is hoped that such a study may be made soon in order to establish the proper temperature range to be used in computing preferred orientational values.

The conclusion of Turner and Ch'ih that there is no appreciable change in fabric that can be attributed to crystallization after heating to 700°C. is important; it is probable, however, that incipient recrystallization does occur. The evidence from thermal analysis suggests that a slight change in the rate of change of α occurs in the vicinity of 350°C.; and for this no other explanation has been found. Turner and Ch'ih make a similar suggestion regarding apparent elimination of broad

twin lamellae and reduced percentage of sets of lamellae that have a spacing index of 20 or more. They do, however, reserve decision as to the reality of such changes. Certainly the changes in both fabric and expansion characteristics are small, but the fact that they are recognizable is important. Later work may reveal their full significance.

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DISCUSSION

ORIGIN OF PIMPLE MOUNDS, by E. L. Krinitzsky

This paper, American Journal of Science, vol. 247, pages 706-714, is one of many in which an author supposes that micro-relief mounds of a single type may have different origins in different regions without change in essential characteristics except a variation from fine sand and silt to gravel and cobble in the coarser components of the material. In this case it is also, more or less tacitly, implied, without full consideration of details, that soil development and accompanying mass wasting will level such original differences as between streamlined, fine-grained and cross-bedded eolian sand dunes, sub-aqueous "dunes" in the form of river bars with moundy elements, and mounds made by rodents.

Although the reviewer believes that this paper was outdated when it appeared, it is desirable to discuss it, because it is typical of a large class in the literature and because it is instructive in several features. The revival of interest in the pocket gopher theory began with V. B. Scheffer's restatement (1947) and continued mostly in the "Scientific Monthly" in 1948 with the resurrection of F. C. Koons' highly significant report of his years of observation of the growth of pimple mounds in Texas by the agency of pocket gophers, and the discussion by several others of the definitive role of poor surface and underground drainage in leading the rodents to build small "winter mounds" to hold the nest and food-hoard above winter floods, resulting in the eventual development of pimple (or mima) mounds by repeated additions of soil thus brought to the nest area from locations always at the margin of the growing heap. The "winter mound" is a weak structure, commonly destroyed by animals or the weather by the time it is needed again after the first flooding.[1]

Krinitzsky has missed (1) the critical item of mound structure, *the bi-convex lens of top (A zone) soil*, forming a wholly abnormal thickening of the top soil, inexplicable under any origin except the sort of diligent underground cultivation done only by the pocket gopher, among burrowing animals of a size adequate to produce these mounds and to move gravel, (2) the present writer's statement that (Price, 1949) the bi-convex structure has been found to be characteristic of the mounds in all regions of occurrence of the type—nearly every state west of Mississippi River—and (3) that the mounds do occur abundantly (*contra* Krinitzsky, p. 712) where gophers live in thin "residual" soil above hard rocks and soil

[1] Full documentation of this discussion is not attempted, being covered in the papers cited here and by Krinitzsky.

claypan. The rocks include basalt flows and eolian pavements and the claypans occur in California and also in the Gulf Coast, where Krinitzsky seems not to have seen them under mounds. He also misses entirely the later development of the gopher theory in which a "shallow lying base of gravels" is found to be by no means an "integral requirement of the gopher-hypothesis" (p. 712), any feature denying rainfall a chance to drain away being sufficient.

Krinitzsky seems not to have studied the soil zonation of pimple mounds widely, as he says that the material of the mounds is "entirely distinct from surrounding soils" (p. 706), a statement not borne out by careful examination of the soil in areas where mounds are freshly developing, but true in part where the gophers have completed their task of collecting all the available top soil into mounds. Even then, there are similarities, and in early stages almost identities, between the B and C zones and claypan and hardpan layers of the mound and inter-mound areas.

Krinitzsky has been misled by the excellent preservation of Prairie (younger Beaumont) microrelief topographic grain (plates 1, 3, 4) into thinking that pimple mounds are only slightly altered features of Pleistocene age. He has missed the important unconformable relationship of pimple (mima) mounds with the Pleistocene and some Recent deposits. The mounds are far more perfectly preserved than are most similar microrelief features of small size and loose, sandy composition but of Pleistocene age. They also occur in vast numbers on worn-down distributary ridges (natural levees) of Montgomery (older Beaumont) and some Prairie deltaic plains in Texas and Louisiana, where from 10 to 25 feet of height of the levees has disappeared. They also occur in numbers on Pleistocene depositional surfaces being distributed in relation to modern surface features imposed on them, such as rain ponds and shallow drainage swales of recent origin.

Krinitzsky misses in the literature the highly significant relationship of mima mounds to gully divides. These small ridges are thickly studded with mima mounds in parts of most states where the mounds are known. Such divides range in age from dissected, inactive Pleistocene features of dissected alluvial fans along the eastern side of the Central Valley of California, to gully divides now in growth on rolling hillsides of eastern Texas and adjacent Louisiana. The mounds widen the divides, interfering with the normally straight courses of the gullies and producing entirely abnormal sinuosities. These same distinctive types of fan-shaped or radiating gullies of alluvial fans and rounded hill tops occur

[3] "Recent" is retained for the Gulf Coast, where detailed correlation with the glacial section is not yet accomplished.

abundantly in states east of the Mississippi River, where the writer has examined them from the air lanes, but without anywhere showing any tendency to develop the sinuosities of the mound-occupied gullies. Reticulated gully systems do not occur along the air lanes of the East, so far as the present writer has been able to observe, with any regular system of mound-formation of mima type such as would be required by the hypothesis of F. A. Melton (1935). Surely processes producing natural mounds west of this river should operate under similar circumstances also east of it, where gophers are absent.

While existing mima mounds are believed to be of late Recent origin, it is possible that there were Pleistocene mima mounds and even that individual mound colonies have remained ***in situ*** and under occupation by gophers since then. However, the amount of reduction of sandy surfaces during the development of mature soils is commonly appreciable and we know that some of the Pleistocene depositional plains have minor surfaces of erosion on them. This subject is speculative. If Pleistocene mima mounds occur, the rodents must have kept them in repair during long periods since then. Their habit of decorating the mound surface with numerous small piles of soil keeps existing mounds fresh and relatively smooth-contoured.

With regard to the "eolian dune" hypothesis, Krinitzsky assumes that the mima mounds seen in plate 4 abundantly dotting beach ridges and parts of the abandoned lagoonal plain of the Ingleside Pleistocene shoreline terrace at Smith Point, near Galveston, Texas, formed as small mound-shaped dunes on beach ridges. The writer has an intimate familiarity with the barrier islands of the western coast of the Gulf of Mexico from southwestern Louisiana through Texas to Tampico, Mexico. Nowhere is such a relationship found in active beach ridges, although impermanent low shrub-coppice mounds form on the bare upper parts of active beaches, but without being preserved on the older, stabilized ridges. The habit of dune formation on barrier beaches of this coast is as follows:

In the humid and moist sub-humid regions, the Recent and Pleistocene beach ridges of prograded beach plains are low, regular, relatively even-topped and without dunes, except as stated above. In the dry sub-humid and parts of the semi-arid regions, eolian sand loads the vegetation of the beach ridges, building up smooth, wide foredune ridges that rise above and cover two or more beach ridges with the intervening swales. The ridges do not support other dunes upon them and blowouts are rare. Both conditions are found on the Recent barrier island between Galveston and Corpus Christi, pimple mounds being absent.

Where sand supply is large and moves actively in the wind, as is here the case only in the semi-arid region, foredunes rise to maximum heights and blow out where over-steepened. U-dunes, elongate blowout dunes, amputated lag-ridge arms and dunes irregularly eroded by storm waves all occur stabilized, but without anything of pimple mound type. The beach ridges are obliterated here and the resulting topographic pattern is irregular and of a much larger grain than pimple mounds. It would not yield a pimple-mound type of topography on weathering. On the Pleistocene barrier islands of the coast in this semi-arid region, the islands are built up 15 to 20 feet or more higher (than the sections in the humid region) by eolian materials and their surfaces are old dune plains of smooth contours. The dune remnants are broad and indistinct, virtually indeterminate, the plain being dominated by transverse blowout swales somewhat like broad, open yardang grooves.

The somewhat reticulated microrelief of low sandy ridges with mound-like portions and isolated ovals and mounds shown in plate 2 and said to have formed as sub-aqueous "dunes" in Mississippi River makes a welcome contribution to the knowledge of subaqueous microrelief and merits still further detailed illustration besides that shown in plate 5. If such relief is preserved in gopher-occupied areas it would doubtless be quickly occupied by the rodents and, if drainage were poor, might become decorated by mima mound development. However, unless mima mounds were developed here, there would be no formation of bi-convex lenses of top soil. ***Without such soil structure, no mounds, even if of suitable size and distribution, belong to the category mima, or pimple.*** This is a feature that must be taken into account by the proponents of polygenetic origin for mima mounds. Unfortunately, most geologists are not versed in the fundamentals of soil science and are unfamiliar with the field relationships of soil zones.

The listing of pimple mounds in floodplains in Tennessee by Krinitzsky (p. 707) merits further investigation, as this is the first record from a state that extends east of the Mississippi River (Price, 1946, figs. 1 and 2).

The mound-like or circular mottles of the glacial swell and swale described by Gwynne (1942) cited by Krinitzsky (p. 710), from Iowa seem to be of a coarser grain than mima mounds, the diameters of the supposed mounds ranging up to 600 feet. If these are the mottles of leveled ridges and mounds, it is strange that no unleveled areas remain. Mima mound mottles on leveled farm lands have the same appearance from the air, but seem to be smaller.

The present knowledge of mima mounds is the result of a thorough exchange of views and information between research workers

and field surveyors working in rodent control, soil structure and history, drainage and groundwater, and geomorphology. Little contribution to interpretation was made by the greater number of the papers published before W. W. Dalquest and V. B. Scheffer announced their findings with regard to the close relation between pocket gophers and mima mounds. Only M. R. Campbell (1906) among the early workers saw that organic deposition was necessary to explain the abnormal thickening of the top soil in the mounds. Many writers have evidently written as though the mounds were a mere scientific curiosity and have treated them lightly, rushing to give a "solution" on the basis of hearsay, examination of photographs, or external examination of mounds in the field. When, as in the present case, an author has hit upon a seemingly satisfactory analogy for the area that he knows best, too often he has been content to let it go at that, resolving the difficulties raised by distant mounds by assuming polygenetic origin. Polygenetic origin for identical features even of this simplicity must be rare indeed.

In this article and the present writer's discussion of it, two cases of the double use of a common geomorphic term between geologists and hydrographers or oceanographers is evident. "Dune" is used interchangeably for eolian and sub-aqueous features by hydrographers, following Gilbert. Geologists now must write "barrier island" instead of Douglas Johnson's "offshore bar" because oceanographers use the latter term in its original, simple meaning of a submarine bar. Confusion has arisen in both cases, neither of which should have occurred.

The writer is in harmony with Krinitzsky's discussion of hypotheses of pimple mound origin other than those noted in the foregoing paragraphs (Price, 1949). W. ARMSTRONG PRICE

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REPLY

In proposing a polygenetic theory of origin for pimple mounds the writer has not dismissed gophers as being builders of these features. However, their universal importance has been brought into question.

The natural mounds referred to in western Tennessee are the "sand blows" described by M. L. Fuller (U.S. Geol. Survey Bull. 494, Washington, 1912) as having originated by extrusion during the famous New Madrid earthquake of 1812-13. Fuller distinguishes these features from mounds of other origin.

Price in his discussion brings out a very important point. He states that rodents develop a bi-convex lens of top-soil and that "*Without such soil structure, no mounds, even if of suitable size and distribution, belong to the category mima, or pimple.*" Hence Price makes it a matter of definition that internal characteristics as well as surface appearances be considered before a mound may be classed as a "pimple." If this position is taken, certain natural mounds would be excluded from this category. Also mounds of other origins, but which later have been occupied and partly preserved by gophers, would not be interpreted through their original genesis but solely by their gopher history.

Perhaps it is desirable to refine definitions by setting close limitations. If a definition of this sort becomes accepted, it must be admitted that some differences on the origin question would be clarified.

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REVIEWS

Principles of Electricity and Magnetism; by G. P. Harnwell. Pp. xvi, 670. New York, 1949 (McGraw-Hill Book Co., Inc., $6.00).—This is the second edition of a standard text used in upper division courses on electricity and magnetism. First published in 1938, it has won its way among text books because of its comprehensiveness and its full treatment of applications. The new edition preserves the advantages of the old but brings the contents up to date.

On the whole the new book accentuates the subjects of electronics and high-frequency radiation, and it does justice to the new developments in accelerator research. Specifically, the following sections have been added to the older text:

- Forces on conductors and dielectrics
- Electron structure of crystals
- Magnetic induction accelerators
- Feedback amplifiers
- Very high-frequency oscillators
- Propagation of electro-magnetic waves in metallic enclosures

The size of the book has grown from 619 to 670 pages.

HENRY MARGENAU

Heat Transfer, Vol. I; by Max Jakob. Pp. xxix, 758; numerous figs. New York, 1949 (John Wiley & Sons, Inc., $12.00).—This is an excellent advanced text and reference volume covering all aspects of the subject of heat transfer. A good knowledge of the calculus and differential equations is necessary for the understanding of this book, but the treatment is not highly mathematical. Considerable space is devoted to the explanation of the physical properties of matter that play a role in heat transfer, and there are well-chosen admixtures of empirical material and descriptions of experimental methods and techniques.

The value of this book as a reference work is enhanced by the unusually detailed and logically-ordered table of contents, as well as by the fairly complete alphabetically-arranged bibliography. The author obviously has a full knowledge of both the fundamental physics and the engineering applications of heat transfer, and both are equally well presented. W. W. WATSON

Biochemical Preparations, Vol. I; by H. E. Carter (Editor-in-Chief), E. Ball, C. Niemann, R. R. Sealock and E. E. Snell. Pp. xi, 76. New York, 1949 (John Wiley and Sons, Inc., $2.50).—This is the first volume to appear in a prospective series designed

to provide authoritative and thoroughly checked preparations used in biochemical research. It is hoped that this series will achieve for biochemistry what *Organic Syntheses* has done for organic chemistry. To further this purpose, the editors of *Biochemical Preparations* have conferred with the editors of *Organic Syntheses* in order to avoid those mistakes which are frequently made in starting a new series. It is the intention of the editors to publish a new volume every 12 to 16 months.

This series will cover the preparation of substances which are not readily available commercially, but which can be prepared from available starting materials. Isolation methods from natural materials will be emphasized, but where synthetic methods are more suitable these will be given. In addition, techniques of general application in preparative work will be included.

The present volume details sixteen preparations of which four are synthetic, *e.g.*, *p*-hydroxyazobenzene-*p*'-sulfonic acid and DL-glyceraldehyde 3-phosphoric acid. Of the other preparations six are for various amino acids such as L-alanine, L-glutamine and D-tyrosine, and three are for nucleic acids (adenosine triphosphate, diphosphopyridine nucleotide). In addition the isolation of the carotenoid lycopene from tomato paste and the preparation of crystalline lysozyme (globulin G_2) from egg white is given as well as several less readily classified substances.

The reviewer has found the presentation of the preparations to be remarkably lucid, precise and complete. Expected yields, conditions, manipulative techniques, explanatory foot-notes and references to the original literature are given. The edition is singularly free of typographical errors and is well indexed.

ALFRED H. FRYE

Geology of the Sudan; by GERALD ANDREW; chapter VI (pp. 84–128) of *Agriculture in the Sudan*, edited by J. D. Tothill. Oxford, 1948 (Oxford University Press, 42 shillings).—Geologists should know of this clear and concise summary of present knowledge of the geology of the Anglo-Egyptian Sudan. What is known of the basement complex and of the overlying flat-lying largely arenaceous sedimentary rocks (Carboniferous? to Cretaceous) is indicated, but special emphasis is placed on the late Cenozoic deposits, on recent processes of erosion and deposition, and on soils and soil formation. The description of the sediments in and around the semi-arid basin in the southern part of the country (swamp and flood-plain clay, dune sand, lateritic ironstone and related ferricrete sandstone and grit) will be of interest to students of continental sedimentation.

JOHN RODGERS

The Snellius Expedition: Vol. V, Geological Results; Part 3, Bottom Samples; by G. A. Neeb and P. H. Kuenen. Pp. 268; 16 plates, 83 figs. Leiden, 1943 (E. J. Brill, 30 guilders (appr. $8.00)).—This publication has been available in America since the war, but in view of its importance a belated review seems in order.

The report presents the results of the study of some 840 bottom samples taken in 1929-1930 from the Dutch vessel Willebrord Snellius in the eastern part of the Netherlands Indies. In this part of the archipelago, many large and small islands stand on ridges separated by basins 2 to 4 miles deep; in other words the area is neither strictly continental nor strictly oceanic. To many geologists, it is a modern counterpart of the "real" (eu-) geosynclines of the past.

In an introductory section, Dr. Kuenen describes the taking of the samples and discusses several topics of general interest, notably the statistical correlations found between organic matter, calcium carbonate, depth, and distance from shore. In the main body of the report Miss Neeb describes and classifies the samples and discusses the source and deposition of the bottom sediments. The principal types recognized are volcanic mud, terrigenous mud (derived from several types of terrain), mixed volcanic and terrigenous mud, coral mud and sand, and *Globigerina* ooze. Typical oceanic red clay is recorded from the Mindanao trough at the edge of the Pacific basin, not from the basins within the archipelago.

The data are summarized on an admirable map (scale 1:4,000,000) showing the distribution of the deep-water deposits. The distribution pattern is complex and is controlled not by a single factor such as depth or distance from shore but by the interaction of several, primarily the proportions of different materials supplied (volcanic ash, debris from the islands and from coral reefs, and shells of pelagic organisms) and the marine currents, secondarily the configuration of the basins, especially their relative isolation, the depth, and the distance from the source of the materials.

To a geologist of the future, the present sediments would display rapid and bewildering facies changes. Not improbably he would recognize resemblances to the rocks of at least certain pre-Recent geosynclines, such as the Alpine, though the pattern would perhaps be less linear. To geologists of the present, Dr. Kuenen and Miss Neeb have made available an excellent discussion of such rocks in the making. JOHN RODGERS

Memoir on the Systems Formed by Points Regularly Distributed on a Plane or in Space; by A. Bravais. Journal de l'Ecole Polytechnique, Cahier 33, Tome XIX, pp. 1-128, 1850. Translated by

AMOS J. SHALER, Massachusetts Institute of Technology, 1949. Memoir No. 1 of The Crystallographic Society of America ($3.90). Pp. viii + 114; 42 figs.—In this work Bravais demonstrates the properties of space lattices and plane lattices (nets). He leads logically to the 14 well-known Bravais lattices, and in the last section, polar or reciprocal lattices are defined and their properties developed.

This memoir is an important part of the foundation upon which modern crystallographic theory now firmly rests; it should be known to every crystallographer, be he interested in crystal morphology or structure, in scientific philosophy or in engineering applications. An early introduction to this work should therefore be a part of every student's course, for it will inevitably lead him to a better understanding and appreciation of the subject, and hence to more fruitful research and applications. That Bravais himself realized the application of lattice theory to crystals is shown in his concluding remarks, wherein he refers to this work as forming, "as it were, the preface of the theory of crystallography . . . " He surmised that a molecule or group of molecules would be associated with each lattice point, exactly as Laue's discovery proved 65 years later.

Bravais' presentation of his thesis in the shape of definitions, theorems, problems, corollaries, and scholia is formal, but the book is in fact surprisingly readable, and the method of presentation simply adds unusual flavor for modern readers. A few readers will find this feature annoying at first, but with a little practice, the form is as easily readable as any other for the presentation of the subject.

Mr. Shaler's translation not only gives English readers the content of this otherwise rarely available publication, but even captures some of the detached scientific spirit in which Bravais and his contemporaries usually wrote.

HORACE WINCHELL

Science and the Moral Life; by MAX OTTO. Pp. 192. New York, 1949 (A Mentor Book, paper, $.35).—In his brief preface to this book, E. C. Lindeman of Columbia University characterizes Max Otto, professor emeritus of the University of Wisconsin, as "the 'homespun' philosopher." The expression is not wholly apt in this case because it has come to mean men like Will Rogers, often excellent, even great, in their way but men whose main talent is for the witty expression of the obvious or for well-turned support of popular prejudices. On rare occasions, Otto does skirt this field of "homespun philosophy" (perhaps in "With All Our Learning" or in "The Hunger for Cosmic Support" among essays in this volume), but

as a rule he is antipathetic to it. Lindeman's point is that Otto is not a speculative or academic philosopher but is one who expresses philosophy in terms of human actions and problems. His message is not banal and it is far from a mere restatement of folk beliefs.

The message is one of great concern to scientists and to the world. As expressed in one of these essays, Otto's view is that science, as historically developed in isolation from human emotional problems and with a tradition of "ethical neutrality," tends to destroy mankind. The alternative that mankind should, before it is too late, destroy science cannot be seriously considered. Otto's solution, in this particular essay ("Scientific Method and the Good Life") is "untrammeled study of fact in union with the hunt for the most promising means of general happiness." His pessimistic view of science here and more particularly in the most gloomy of the essays, "The Ethical Neutrality of Science," seems to be based almost wholly on the physical sciences. Elsewhere, more clearly than in the passage quoted, his solution of the dilemma involves recognition of the social role of all the sciences and extension of, essentially, the scientific method to the problems of human welfare (moral as well as material) and of ethics.

The book is a collection of chapters from previous books and of separate essays, all but one of which have been published elsewhere. In date they range from 1924 to 1945. Although all chapters bear on somewhat the same basic human problems, the arrangement may confuse the development of Otto's thought. The last chapter (followed by a peroration as "conclusion") is actually the earliest writing in the book and is less mature, also shows less insight into science, than several previous chapters on nearly the same subject. A change in approach is visible, for instance, even in the short time between writing "Realistic Idealism" (published as a book chapter in 1940) and "Scientific Humanism" (1943). The book of 1940 was suspicious of science, even antagonistic to it, and proposed an antidote in philosophy—Otto's philosophy, that is, geared to observation of nature and to human realities. But this is, in fact, rather a scientific than a classically philosophical approach, as becomes explicit even in the title of the later essay. There he more clearly espouses not a philosophical remedy for the ills of science but an extension of scientific method "to moral and social problems of every kind."

Since 1943 some of the dangers stressed by Otto have become more acute. Physical science is triumphant and is becoming more and more a destructive or enslaved instrument of the state. (This possibility was inadequately evaluated by Otto, who earlier favored forms of control of science by society which are particularly open to this danger of perversion.) On the other hand, the social respon-

sibility of science has been increasingly recognized by scientists, including many of the more thoughtful physical scientists, and there has been an intensification of effort to interpret scientific results in human, including ethical, terms.

Another recurrent theme in these rather miscellaneous essays is that of the nature of man and especially the problem of the fundamental "goodness" (in some sense) or dignity of man *versus* his basic sinfulness or vileness. Some dominant religions demand the latter view: hence "original sin" and the requirement of redemption. A similar orientation has been derived from scientific emphasis on the animality of man and his origin from lower forms of life. Oddly enough, orthodox theology has rejected this apparent support for its view. It wishes to consider man vile, but not for that reason. Now many scientists believe that their findings refute the scientific denigration of man's basic nature. (Julian Huxley, for instance, attacks the fallacies of the "Nothing-but" school, as in "Man is nothing but an animal," and Maslow insists that the deepest and in a sense most primitive human impulses may also be the most desirable and ethically best.) Thus science, for these students, and religion, for those who believe in original sin, no longer support the same view for different reasons but emphatically contradict each other as to the non-sinful or sinful nature of man. Although he does not express this issue quite so flatly, the same sort of trend results in Otto's biting attack on authoritarianism and supernaturalism in religion. The fact that this essay is the only one in the book not previously published (it was read from manuscript at a conference in 1948) may be significant, even though Otto does not name the particular churches that he clearly had in mind.

The most important point about all this is probably the implication that even such traditionally theological problems are subject to study by scientific methods. They move, indeed, within the proper province of science as science matures beyond preoccupation with the merely physical and loses its strange obsession that objectivity of judgment, which is necessary to scientific method, also means ethical neutrality, which makes science non- or even anti-human. Otto does not put things in quite this way. He is, after all, a philosopher and not a scientist. But he considers much of classical philosophy, its more speculative, not phenomenally controlled parts, as sterile and empty of real subject matter, and when he pleads that scientific method be applied to the still living parts of philosophy he does, in effect, extend the domain of science over this field. This is the next needed step in the struggle of man toward a truly rational interpretation of the universe and of himself.

The scientist may ask one final question. If these subjects are considered a proper concern of science and subject to scientific

method, why is the book written by a philosopher and not a scientist? The answer is that such a study requires a new kind of scientist and that few have yet appeared. Philosopher Otto should be the forerunner of ontologist X of the future, a scientist.

The first issue of such a volume in a thirty-five cent newsstand edition is also a hopeful sign for man's intellectual progress.

G. G. SIMPSON

The History of Nature; by C. F. VON WEIZSÄCKER. Pp. vi, 192. Chicago, 1949 (The University of Chicago Press, $3.00). Translated by F. D. Wieck.—Here a young man of great scientific genius unveils beliefs and convictions that have inspired his researches and have kept him sane in the whirlpool which was Nazi Germany. The book is essentially a philosophic treatise dealing with problems of the natural sciences. Its philosophy is not systematic, nor is it presented in a manner aiming at specific goals. But the sincerity of the discourse, the depth of concerns for issues that lie conventionally outside the disciplines of natural science, make the book impressive and memorable.

The subject matter of the book attests to its unusual character. For it contains chapters on "Life," "The Soul," Man's "Outer and Inner History" besides the more customary topics of time, space and astronomy. Interesting facts, many of them new to this reviewer, are included in the purely scientific parts of the book, all of which are pleasant to read and comprehensible to the layman. The author is convinced of what he calls the "historic character of time." His time is similar to Bergson's; its progress is regulated by the Second Law of Thermodynamics, and it has a beginning as well as an end. The reasons for such beliefs are simply presented in this book.

Much space is devoted to the development of stars. This is the subject which will doubtless elicit greatest delight from the reader; it is well presented and beautifully illustrated by plates as perfect as any I have seen.

In final appraisal, one might say that Weizsäcker's book immerses the elements of modern physics and astronomy in the deep current of existentialism which characterizes European philosophy of our time.

HENRY MARGENAU

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ERRATUM

In the paper by Harold D. Fox entitled "Structure and Origin of Two Windows Exposed on the Nittany Arch at Birmingham, Pennsylvania" (March, 1950), page 157, line 13, should read:

"plunging southwest end of the Nittany arch has been named."

American Journal of Science

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GRANITIZATION IN THE SWAUK ARKOSE NEAR WENATCHEE, WASHINGTON

HOWARD A. COOMBS

ABSTRACT. In the geographical center of the State of Washington, the Swauk formation is a large lithologic unit in the eastern portion of the Cascade Range. This formation is composed essentially of arkoses and sandstones with lesser quantities of clays, shales, and conglomerates, all of Eocene age.

Along the axis of an anticline two miles south of the city of Wenatchee, the arkoses have been transformed locally into a rock having the composition and texture of many granodiorites. The various steps in the granitization process can be traced from the initial stages wherein the quartz is enlarged by secondary growths and the plagioclase is rimmed with clear albite, to the final stage resulting in a coarse-grained rock of interlocking crystals devoid of interstitial matter.

In the intermediate stages, the clastic grains still reveal their original shapes although they have incorporated or rejected much of the interstitial matter, which is now in the form of a granular matrix. The resulting textures show crenulated crystal boundaries with numerous inclusions or intergrowths, or both.

This locality is thought to be noteworthy because the successive steps in the granitization process are preserved in the textures of the rocks, and because the process was carried on at low temperatures with an extremely small amount of solutions needed.

INTRODUCTION

THE subject of granitization has received ever-increasing attention during the last few years and from many divergent points of view. The purpose of this paper is to describe a locality where feldspathic sandstones and arkoses have been transformed into rocks having the texture and composition of many granodiorites. The writer follows the definition for granitization given by Read (1948): "The process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage." It is realized that this is a more limiting definition than those proposed by many others, but it defines precisely the process of granitization in the arkoses near Wenatchee.

Fortunately, in the rocks here described, the various steps in the granitization process are preserved in the textures and minerals of the rocks, and it is only in the most advanced stages that the original clastic fragments lose their identity in an allotriomorphic to hypidiomorphic granular rock.

The composition of the original arkose is strikingly similar to that of the granitized product. Thus little transfer of material was required. At best, the metasomatic addition of a small quantity of soda (perhaps in the magnitude of one or two per cent) was all that was necessary to bring about the complete transformation.

Perhaps the most remarkable feature in the granitized rocks of Wenatchee is the low temperature involved. As granitization is a metamorphic process, the environmental conditions under which these rocks were transformed could be described as corresponding to Grubenmann's epizone or "upper" mesozone of regional metamorphism. The evidence for the temperature of transformation is the mineral association, which changed but little from start to finish. The proof of the transformation from a clastic to a granular rock of interlocking crystals consists of the textures and their changes from one stage to the other. For this reason the textures are emphasized in this paper.

THE SWAUK FORMATION

Areally, the Swauk formation forms a large and well-defined lithologic unit in the vicinity of Wenatchee. The rocks, although varying considerably in grade size, nevertheless have a rather uniform mineralogical composition. Quantitatively the most abundant types are white to buff-colored arkoses and feldspathic sandstones. Shales and clays are of lesser importance and the least abundant beds are coarse conglomerates. Except for local zones of granitization, silicification, or beds containing a calcareous cement, the rocks are rather loose and friable.

Estimates of thickness (Smith, 1903; Chappell, 1936) range from 3,500 feet to over 9,000 feet, depending on the locality where the sections were measured. The true thickness is most difficult to determine because of the lenticular character of the beds, the lack of well-defined markers, and the locally occurring isoclinal folding.

In the area of granitization, it may be assumed that the thickness is several thousand feet, for an oil well one mile to the south along the anticlinal axis indicated on the sketch map has penetrated over 4,000 feet of Swauk sediments.

On the basis of paleobotanical evidence, the Swauk formation has been placed tentatively in the early Eocene.

Structurally, the Swauk rests unconformably on the Swakane gneiss, which has been considered as pre-Ordovician in age (Smith, 1916, and Waters, 1932). Shortly after their deposition and presumably in later Eocene time, the Swauk beds were folded into a series of anticlines and synclines whose axes trend generally in a northwest-southeast direction, which is common to the major structural trend of all western Washington.

It is thought that the most pronounced folding in these sediments took place immediately after their deposition, perhaps as early as in mid-Eocene time. In the Mt. Stuart region to the west, the folded and partially eroded surface of Swauk sediments is covered by an Eocene basalt flow known as the Teanaway basalt. In the Wenatchee area, the folded and eroded Swauk surface is covered, in part, by the Yakima (Columbia Plateau) basalts of mid-Miocene age. The basalts together with the underlying sediments were folded into broad arches in post-Miocene time.

In the immediate vicinity of the granitized zone, the Swauk sediments are folded into an anticline with dips along the flanks varying from 35 to 65 degrees. The rising solutions were undoubtedly controlled by the anticlinal structure, and now the long dimension of the granitized zone coincides rather closely with the anticlinal axis.

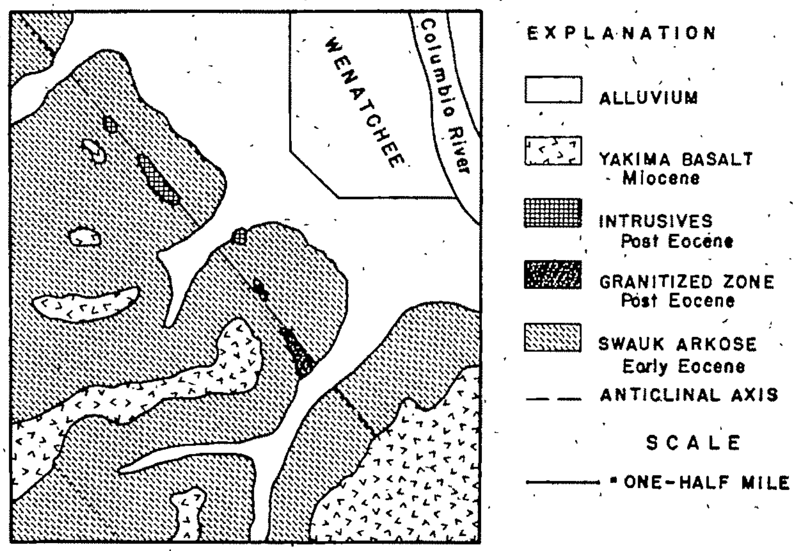
INTRUSIVES

To quote Chappell (1936), "the complex assemblage of igneous rock bodies intrusive into the Swauk formation is regarded by the writer as the most extraordinary of all the geologic features in the map area." In many places, the intrusive bodies are too numerous to be mapped separately. They vary from dikes a few feet in width to laccoliths over 400 feet thick. The intrusive rocks are usually andesite porphyries and basalts. However, all varieties exist from the more basic to the more acidic types, including masses of perlite and necks

of porphyritic rhyolite and dacite. In addition, many zones of strong hydrothermal alteration and intense silicification exist within the area. The small intrusive bodies near the granitized zone are indicated on the geologic sketch map (modified after Chappell).

While the writer was in the field with Chappell approximately 15 years ago, an interest was kindled in some of the unusual features of these "intrusives." Recent field work and petrographic studies together with many chemical analyses of nearby rocks, now reveal the true nature of many of these masses. This paper represents the first in a series describing the petrography of this interesting area. Later papers will deal with the petrography and petrology of nearby "intrusives."

From structural evidence, it is thought that most of the intrusives were more or less contemporaneous and were perhaps all emplaced in mid-Eocene time. The granitization probably occurred simultaneously with the emplacement of adjacent related masses. It is well known (Turner, 1948) that andesite porphyries or even basalts could provide the small amount of soda necessary for the granitization process. How-



GEOLOGIC SKETCH MAP

ever, even closer to the granitized zone are felsite porphyries and perlites.

PETROGRAPHY

Swauk Arkose

The Swauk arkoses and arkosic sandstones are composed of angular to subangular grains of quartz and plagioclase with some microperthite and orthoclase, usually varying from 1 to 2 mm. in diameter. The cement is silty material composed of grains of quartz, biotite, and muscovite, and argillaceous material with an iron oxide stain.

The amount of quartz varies considerably. Locally, almost pure white sandstones with a siliceous cement occur. In the arkoses, quartz may make up as little as 15 per cent of the rock. All gradations in quartz content exist between these two extremes. In the area south of Wenatchee, the quartz shows wavy extinction and is water-clear.

The feldspars, in contrast to the quartz, exhibit varying degrees of turbidity caused by the abundance of minute sericite shreds, a little kaolinitic material, and some iron oxides. The turbidity is not so great, however, as to obscure albite twinning or zoning, for either or both may be seen in most of the clastic grains. Most of the plagioclase grains contain about 75 per cent Ab, but the composition varies considerably in the zoned varieties.

Orthoclase and microperthite also occur as detrital grains, but are not common.

The cement between the grains is composed mainly of clear, angular pieces of quartz ranging in size from dust to fine sand; plagioclase; and flakes of brown biotite and clear muscovite, all of which are scattered in a turbid kaolinitic material.

The microscope also reveals a slight degree of cataclasis. Biotite and muscovite may be wrapped partially around quartz and feldspar grains. It is thought that the shearing was contemporaneous with the folding of the Swauk sediments.

The Granitized Zone

Approximately two miles south of the city of Wenatchee is an area of prominent spires extending from the bottom of the valley at 1,250 feet to the top of the ridge over 2,000 feet high. The spires rise as isolated jagged points over 50 feet above their immediate surroundings in a linear pattern near

the top of the divide. Near the bottom of the valley, the eastern edge of the granitized zone is marked by a wall over 100 feet high and 300 feet thick and containing numerous quartz veins.

The contacts between the granitized zone and the relatively unmetamorphosed Swauk arkose are surprisingly sharp laterally. The bedding closely parallels the contact and shale members usually mark the boundary of the granitized zone. Vertically, little change in the degree of metamorphism is evident within as much as 500 feet.

First Stage in Granitization.—The sediments described above have been subjected to metamorphism and as a result exhibit characteristic changes in texture which represent several stages of transformation. The most obvious change is for the rock to become lighter in color. The cement between the grains has been affected most in this bleaching process. The iron oxides were either concentrated into small clusters or streaks or converted into small granules of epidote. Silica was present in excess during this conversion and both quartz and epidote occur together as small veinlets in many of the whitened rocks.

As the iron oxides are removed from the cement between the sand grains, the mass is now seen to be composed of clear quartz, turbid feldspar, partially leached biotite shreds, and clear muscovite. (Some sericite now appears in the cement and in some of the feldspar grains.)

Most striking is the enlargement of the clastic oligoclase grains through the growth of clear albite rims. The rims surround small and large grains alike and have formed sharp projections wherever possible. The delicate projections indicate beyond doubt the authigenic nature of the albite rims. The original shape of the clastic grains of turbid oligoclase is now very conspicuous in contrast to the water-clear albite rims.

Like the plagioclase, the quartz grains began to grow, but they started by adding small radial projections which grew out from the surface of each clastic grain. This structure is very pronounced in those sandstones that have an extremely high original quartz content. In the more progressive phases of the first stage, the silica solutions encroached upon and engulfed neighboring grains of quartz. These growth borders are reminiscent of those described by Goodspeed (1937a) and Misch (1949).

The Second Stage.—Perhaps the most striking feature of the second stage is the enlargement of both plagioclase and quartz grains at the expense of the particles in the cement. Plagioclase commonly has a very large outgrowth of albite on one or more sides of the original fragment. Locally, the added portion is larger than the original grain and may completely enclose the original kernel in an eccentric fashion. The room for the more sodic additions may be found in the space formerly occupied by the cement, and perhaps by the partial solution of the kernel. Neighboring crystals of plagioclase and quartz competed for this additional space for their enlargement.

The resulting texture is unusual in that many of the former interstices are now occupied by clear albite with a tendency toward idiomorphism against clear quartz. The remaining granules caught between the growing crystals are trapped in places, and as a result the larger porphyroblasts have very crenulated boundaries with numerous microgranular intergrowths and inclusions. At this stage, the former boundaries of the clastic grains are still distinctly visible. In plagioclase, the original core is turbid. In quartz, an extremely thin layer of limonitic dust marks the surface of the original clastic grain. The quartz is distinctive in its new outline because of long tongues of new quartz that were added as the growing crystal engulfed quartz particles formerly belonging to the cement. An amoeboid shape of the quartz with long and delicate projections is now typical.

The Third Stage.—This stage is characterized by the complete, or almost complete elimination of the former cement. The larger porphyroblasts of plagioclase, microperthite, and quartz have become enlarged until their edges meet in common boundaries or with a minimum of intergranular material preserved. The intergranular material is now mainly in the form of albite wedges or quartz blebs of indefinite shape.

Simultaneously with the outgrowth of the feldspars, the interior or original kernels have been at least in part attacked by albite solutions. The net result is a rather "moth-eaten" appearance with patches of albite scattered irregularly through the older kernels of plagioclase. The margins of these older kernels are usually embayed and rimmed with new albite, a process begun during the second stage but continuing during the later, or higher, stage.

The net result is that plagioclase crystals present a new granoblastic shape in harmony with the new environmental conditions. The quartz is xenoblastic and characteristically fills the interstices between the feldspars or is intergrown, in part, with the feldspars.

The former cement is now at a minimum, although in all sections examined some is present. The small particles, relicts of the former cement, are present as flakes of muscovite, biotite, or pieces of quartz. These particles are in lines representing their former position around clastic grains and many give an excellent clue as to the former boundaries of the larger clastic pieces.

The shape of many original clastic grains of quartz is marked, even in this third stage, by lines of dust particles. Quartz may be intergrown with the feldspars and form granophyric blebs or the more elongate shapes typical of myrmekites. However, these are not intergrowths in the usual magmatic sense, since this rock never reached a magmatic stage. Rather, they are relict inclusions caught in growing porphyroblasts.

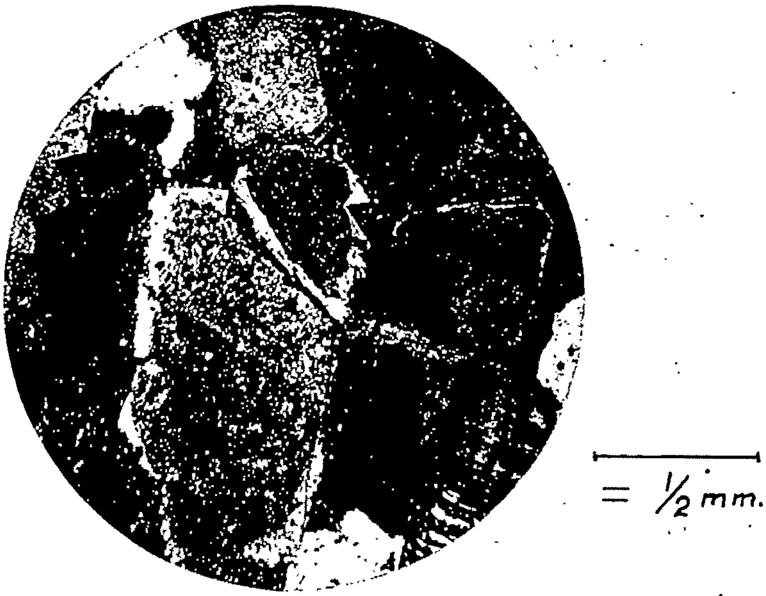
Summary of Textural Changes.—Throughout all three stages, the granitized arkoses have retained traces of their former nature. It is only in the third stage that difficulty might be encountered in distinguishing, texturally, this rock from a so-called "normal" granite.

Perhaps the most significant difference between the granitized rocks described and igneous granites is to be found in the nature of the interstitial matter between the larger crystals. In the cooling of a granitic, liquid silicate melt, quartz is usually the last mineral to finish crystallizing, and it fills whatever space is available. In the granitized arkose, the interstitial matter does not consist of clear wedges of quartz but of seriate particles of quartz, feldspar, and even leached flakes of biotite. These are not the last minerals to crystallize out of a melt *but are the last survivors of an originally clastic cement between larger grains.*

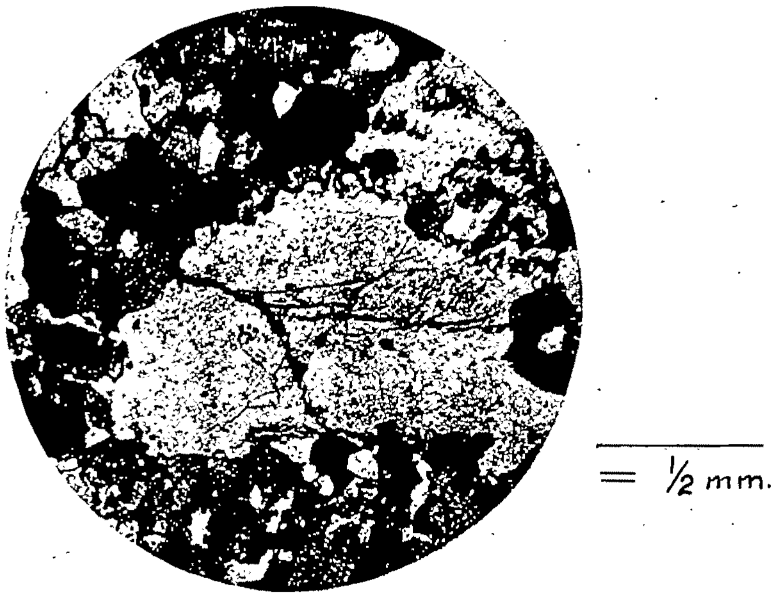
The second point of difference is in the character of the quartz grains. Originally rounded outlines are often preserved in dust-marked patterns with obvious secondary enlargements.

The plagioclase and microperthite, though frequently clear and presenting idioblastic terminations, which may be mis-

PLATE 1

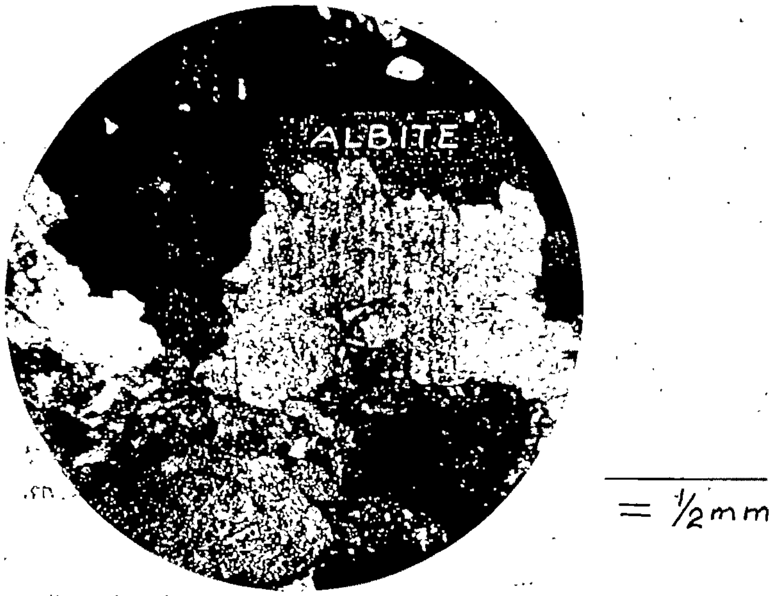


A. Photomicrograph from margin of granitized zone showing clear albite rims with pointed projections surrounding clastic oligoclase and microperthite grains. This texture is characteristic of the first stage.

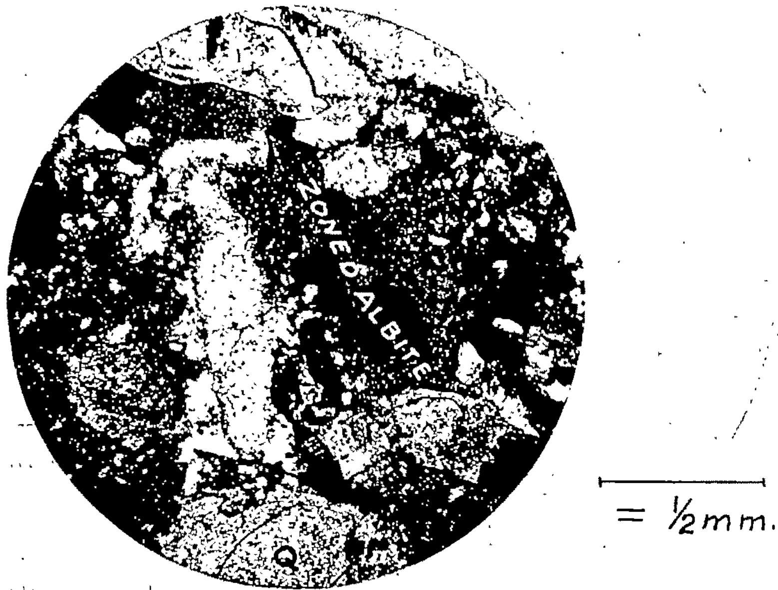


B. Photomicrograph near margin of the granitized zone showing quartz porphyroblasts with definite growth borders. The original cement is clearer, and the grains are larger, than in the initial stage. This is characteristic of the more advanced first stage.

PLATE 2



A. Photomicrograph representing the second stage. The large, light oligoclase grain meets with clear albite in a very irregular contact.



B. Photomicrograph showing second stage. Note dust marking original shape of quartz grain (Q) on edge of photomicrograph. The large grain in the center of the picture has grown beyond its boundary.

PLATE 3

A. Photomicrograph representing the center of the granitized zone, showing quartz in the interstices and quartz intergrown with feldspar.

B. Photomicrograph showing final stages of granitization. The original cement is lacking and in its place are quartz and albite intergrowths. The individual minerals have now reached their maximum size.

taken for an hypidiomorphic granular texture of an orthomagmatic rock, nevertheless show many aberrant features. Portions of the larger plagioclase crystals are out of adjustment when seen under crossed nicols. They tend to have optical continuity (as evidenced by alignment of albite twinning lamellae) but the alignment is not perfect, and some portions of the crystals are rotated with reference to other portions. Further examination shows that these portions may be separated from each other by clear albite or by thin layers of albite, quartz, and mica granules.

Quartz occurs in the feldspars as blebs or myrmekitic patches. Both are the result of inclusion within the growing feldspar porphyroblasts. Conversely, small feldspars are wholly or partially enclosed within the quartz. Again this is the result of porphyroblastic growth, but in this case of the quartz.

Distinctive as these features may seem, they do not differ markedly from many textures occurring in rocks in standard collections and labeled "granites," with the implication that they crystallized from liquid silicate melts. Seriate fabrics, myrmekitic and granophyric intergrowths, poikilitic and hypidiomorphic granular textures are all terms that have been applied to similar rocks.

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COMPOSITION OF THE GRANITES OF WESTERLY AND BRADFORD, RHODE ISLAND

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"... there is no necessary connection between the size of an object and the value of a fact, and though the objects I have described are minute the conclusions to be drawn from the facts are great."

—H. C. SORBY

ABSTRACT. Point-counter analyses of three thin sections cut from each of several specimens of the Bradford and Westerly granites are recorded and a variance analysis of the results indicates that significant differences in composition within hand specimens cannot be detected while differences between hand specimens must be very small.

Quartz values from a much larger collection including small samples of most of the quantitatively important finer-grained calc-alkaline granites of New England suggest that the results for Westerly and Bradford are quite typical.

Theoretical implications of the results are discussed briefly.

A. SOME NOTES ON PETROGRAPHIC HOMOGENEITY

WE often read of uniform or homogeneous rocks, and sometimes of rocks which are fairly uniform or remarkably homogeneous. Yet, if we were called upon to define petrographic homogeneity, nearly all of us would be obliged either to assert that this was common knowledge or to describe the commoner manifestations of inhomogeneity and to specify homogeneity as whatever was left when these were lacking. There is something to be said for this procedure since by it we manage to exclude from the class of homogeneous rocks those which are known to be not homogeneous; but there is after all some difference between classification and description. Among other things, for instance, a man is surely a not-horse, though we still know very little about the class of things which are men when we have excluded from it the things which are horses.

Homogeneity is today a matter of considerable importance to petrology, for the credibility of many current hypotheses hinges on their ability to account for the presence or rationalize the absence of what would be regarded intuitively as inhomogeneities in composition or fabric. This note deals only with the question of homogeneity of composition in its simplest form; it describes the amount and variation in amount of each of the major minerals in two well-known granites. I might as well confess at the outset that no elegant definition of

homogeneity is reached and that what results are obtained must be regarded as applying strictly only to these two granites; but evidence is offered suggesting that similar results may be expected for most of the finer-grained granites of New England.

Studies of variation in composition are usually based on chemical analyses, for so far few petrographers have placed much weight on micrometric results. The petrologist's curious disregard for his own handiwork together with his inveterate and sometimes justifiable respect for the precision of chemical analysis suggest that a study based entirely on microscopic analysis will be welcomed with something less than warmth. Setting aside questions of the precision of the microscopic procedure, which have been discussed elsewhere (Chayes, 1949a), there are a number of advantages of microscopic as opposed to chemical analysis.

The economy of microscopic analysis in time and money is too obvious to require discussion. At present only the spectrograph can compete with it, and the use of the spectrograph for quantitative analysis of the major constituents of rocks is still in its infancy. The cost of chemical analyses tends to favor the use of composite samples, and though this practice may be justifiable in some cases, it sacrifices information about variations in the material from which the composite was drawn.

The microscopic analysis estimates directly the amounts of minerals actually present, and in many cases this too is a very real advantage. Petrographers customarily think of a rock as an aggregate of minerals, as is evidenced by the use of theoretical mineral-like parameters in each of the major chemical-petrographic systems. The first thing a petrographer does with a chemical analysis is recalculate it into something else. It is not always entirely clear just what this something else is or whether it is worth having; but certainly it is not a chemical analysis and, except in the special case of the CIPW norm, the relation between original analyses and recalculated statements is neither simple nor readily predictable (Chayes, 1949b).

The principal advantage of the microscopic technique, however, is that it forces to the surface questions of sampling procedure which do not arise or are left implicit when chemical analyses are used. The remainder of this section is a discussion of these questions.

We never analyze more than a very small part of a rock, and we rarely hesitate to combine as many analyses as we can get into an average value—as we say—for the rock. In what sense may we suppose that the material used in a single analysis represents the rock, or that the average cast up from several such analyses improves the estimate? In the first place, barring gross errors of identification, the material analyzed *is* part of the rock and to this extent represents it. In the second place, the amount of any given rock is finite so that the whole rock *has* some fixed composition and the average of any two determinations will generally be a better estimate of this composition than either (but not necessarily both) of the individual analyses. Now although the average of analyses of many samples drawn from it will probably be a better estimate of the true value than any one analysis, it may have none of the other, and more useful, properties generally associated with means. The estimated composition of the lithosphere is an excellent example; anyone using this estimate and an associated measure of its variability as a basis for inferences about relative frequencies of rocks of different composition would be in for a rude shock. Yet there can be no doubt that at any particular time the lithosphere has a perfectly definite composition and there can be very little doubt that the best way to estimate this composition is to average, in one way or other, as many good analyses as are available.

Except for the object—rather unusual in petrography—of estimating a supposedly constant composition, this type of reasoning yields results which are either trivial or misleading. Clearly our proclivities for sampling and averaging require a firmer foundation, one in which the claim that a sample represents the parent is based on something more than the fact that it is part of its parent and in which an average may be regarded as something more than an attempt to approximate a fixed bulk composition of very little interest to petrography.

However much we sit back and think about it we cannot reach a very clear idea of the rock which is to form the parent universe. In general, about all we know is that specimens from widely distant points in what is thought to be the same mass look much alike. We suspect that they must be rather similar in composition and we wish a measure of this similarity which will permit comparisons with other rocks. It is quite pointless

to try to throw a symmetrical sampling grid over a largely unexposed mass of unknown dimensions, and in this situation it is reasonable to suggest that we will do best to take from widely separated sites as many hand specimens as we can afford and begin our thinking where we begin our quantitative work—at the other end of the line.

Now a single thin section, like a hillside or the lithosphere, has a definite composition, but there will no doubt be errors in any estimate of it. A knowledge of this analytical error is fundamental to all further work and forms the subject of an earlier paper (Chayes, 1949a). The procedure used here is exactly that previously described. The analytical error is satisfactorily approximated by the appropriate binomial.

The samples are collected as hand specimens and it is evident that many thin sections might be cut from the same specimen. The next source of variation to be considered is that between thin sections cut from the same hand specimen. Here the possibilities are almost too numerous to describe and I believe the present inadequacy of modal data is largely attributable to the real or imagined difficulties of evaluating them. Grain size and orientation are probably the chief culprits, but even in hand specimens of fine-grained rocks devoid of visible orientation there might be greater differences between sections cut at considerable distance from each other than between sections taken very close together. These differences might reflect composition gradients in the hand specimen, or they might be due to random variations. Obviously it would take much time to evaluate each of these sources of variation in a single hand specimen, and when a fairly complete study had been made of such a specimen there would still be no assurance that other hand specimens were similar.

For a pilot study of this sort it seemed wiser to obtain a little information from each hand specimen rather than concentrate all the information about intra-hand specimen variation in one or two items of the sample. I therefore had three thin sections cut from each hand specimen: two parallel and as close as possible to each other, the third as distant as possible from and not parallel to the first pair. The closely spaced pair test the kind of agreement which might be expected if an attempt were made to "duplicate" a thin section, while the difference between the closely spaced pair and the distant non-

parallel section provide some index of the range of composition in the hand specimen. It happens that little variation is introduced by the location or orientation of the thin section in the hand specimen, and in subsequent calculations the thin sections from a single hand specimen are given equal weight.

This brings us to the final and what I had suspected would be the largest source of variation, *e.g.*, differences between hand specimens. The argument on this score is purely intuitive and holds only if, as in this case, the rock is sufficiently fine grained that a single thin section provides a pretty fair sample of a hand specimen. If this be allowed, it is reasonable to suppose that whether the composition of the rock varies randomly or according to some geometrical pattern specimens separated from each other by distances of the order of miles or tens of yards will in general differ more than sections cut from the same hand specimen. It turns out that even in these granites, where the intra-hand specimen standard deviation is never as much as two per cent for any constituent, the variation between hand specimens is still very small.

As the samples, though admittedly small in an absolute sense, are nevertheless larger and better distributed than those used in previous work of this type, it seems to me that this result throws a new light on much petrographic controversy. Not only does it open up the prospect of obtaining usable results with what is on the whole remarkably little work, it suggests also that hypotheses requiring extreme variations in the composition of granite in the zone of observation are *ipso facto* suspect. This matter is discussed in greater detail in a later section and is mentioned here only to persuade the reader that the rather unexciting material which follows is worth examining.

Reviewing the discussion from the top down, any description of variation in composition involves at least a threefold stratification of sampling: (1) differences between items from distantly spaced sites, (2) differences between items from closely spaced sites,[1] and (3) differences between estimates of the composition of the same item. The first of these is here taken as the differences between hand specimens; the second as the differences within hand specimens; and the third is the

[1] Further subdivision within step (2) is always possible and often desirable.

analytical error, or precision of a single thin-section analysis. This order of summary makes it convenient to close by discussing a matter quite obvious on intuitive grounds, easy to handle in microscopic work, but rather elusive if chemical or spectrographic procedures are used.

Where all that is required is a mean value, any specimen at all is better than none. If information about variability is desired, however, it is essential not only that the sampling and analytical procedures be comparable ***but also that items in the sample be comparable.*** (This is true, incidentally, even if the information about variability is to be used only as an indication of error in the mean.) In work with thin sections an average based on, say, eight thin sections of varying size is preferable to any single result and probably preferable to the mean of three or four of the sections which happen to be large; but a standard deviation calculated from these results is practically uninterpretable. If, on the other hand, an area of the same size has been measured on each thin section the sample standard deviation is readily interpreted as an estimate of the variability of areas of this size drawn from or existing in this particular rock.

An experimental study of the relation between grain size, area measured, and sample variability would be difficult but very useful, for it is clear that with a fixed area of measurement the range of results will necessarily increase with grain size. I hope to discuss this matter in a later report. There is, however, a painfully obvious practical solution: we want as large an area as possible and with standard thin sections we cannot get a very large one. Each of the measurements described below was made on an area of 3/4 square inch; in most cases this area was in the form of a rectangle 1″ by 3/4″.

Here, too, the microscope immediately focusses attention on a problem common to all methods. In general, statements of the type, "the quartz content of granite *A* varies from *x* to *y*," are quite meaningless, whether *x* and *y* refer to percentages or localities. The granite as a whole contains some definite amount of quartz, and the variability of quartz content found in samples of it will depend on the size (weight, area, volume) of the samples. In this paper all estimates of variability refer to the composition of areas of 3/4 square inch, or to averages of such compositions. Some similar specification

of the sampling unit would seem to be necessary where estimates of composition differences are based on chemical or spectrographic procedures, for if we are to study variability intelligently we must have a pretty clear notion of what is varying.

B. THE GRANITES OF WESTERLY AND BRADFORD

The quarries of Westerly and Bradford (formerly Niantic), Rhode Island, were well described by Dale (1908). Though most of them have long been abandoned they can be located without difficulty from his map (1908, fig. 24), and many of them are shown on the remarkably detailed Carolina and Ashaway topographic sheets published by the U.S. Geological Survey in 1943. The Westerly quarries lie in the eastern outskirts of the town. The Bradford quarries are a little over a mile southeast of Bradford and nearly five miles due east of the center of Westerly. Although the ridge in which the northern Westerly quarries lie extends some two miles east of the center of town, the country between the two quarry areas is mostly under heavy cover.

The Bradford granite contains a little more biotite than most of the Westerly material and is always gray or white whereas Westerly is frequently pink. Except for this the granites are indistinguishable to the eye and although biotite-poor material of Westerly type does not seem to occur at Bradford, gray rock with prominent speckling of biotite may be found easily on the grout piles of the quarries in the southern part of Westerly. Although subsurface continuity of these granites cannot be demonstrated, their close proximity, similar appearance, and identical relation to the country rock (both cutting and enclosing a coarse biotite-rich plagioclase gneiss) certainly suggest a close relation. It is all the more surprising then to discover that they are quite different in composition. Mean compositions, drawn from table 1, are as follows:

Mineral	*Westerly*	*Bradford*
Quartz	27.8	23.1
Potash Feldspar	32.6	27.1
Plagioclase	32.8	40.8
Biotite	3.5	6.3
Muscovite	1.9	1.4
Opaque Access.	0.7	0.7
Transparent Access.	0.3	0.6
Color Index	6.4	9.0

We have to distinguish here between statistical and petrographic significance. These differences in quartz, orthoclase, plagioclase, and biotite are all comfortably significant by statistical standards, but for this purpose it would not matter whether the comparison were of two granites or of a granite with a granodiorite.

(Incidentally, in a collection which now includes specimens from well over 175 quarries scattered through all the major granite districts of New England, of the quantitatively important rocks only Bradford is *at the same time* low in quartz, of comparatively high color index, and much richer in plagioclase than in potash feldspar. Even here, however, the color index is not very high and, as is generally true in New England granites, plagioclase is only rarely more calcic than intermediate oligoclase.)

Both Westerly and Bradford are fine-grained granites. Feldspar and quartz grain diameters are mostly less than 2.5 mm. Biotite flakes are usually several tenths of a millimeter broad in Bradford but much less in Westerly. Muscovite occurs as separate small flakes in both rocks but in Westerly it more commonly replaces plagioclase. Neither rock contains an appreciable amount of sulfides. Transparent accessories include carbonate, apatite, sphene, tourmaline, and deep lavender fluorite. Every thin section contains fluorite and in some, because of its deep color, it is quite prominent; yet of the more than 65,000 points identified in the 48 thin sections used for this study, only two were fluorite. Of the transparent accessories, apatite and carbonate are the most abundant. The latter usually replaces plagioclase.

Plagioclase is seldom free of sericite but the replacement is never extensive. Kaolin is common in plagioclase, and in a few thin sections plagioclase is heavily altered to a complex of kaolin, carbonate, and sericite. This aggregate is extremely fine grained but the bulk of it seems to be kaolin. I believe the kaolinization of plagioclase is chiefly responsible for the pink and flesh tints of much of the Westerly granite, for the alteration is much commoner in sections cut from pink hand specimens than in those from gray or blue ones. So far as I know the Bradford stone is never pink, and kaolinization of plagioclase in it is trifling. In both Westerly and Bradford biotite is not infrequently transformed to green chlorite; a little of the

TABLE 1. ANALYSES OF THIN SECTIONS

Westerly Mineral	Series	Spec. No. 18A18	18A19	18A20	18A21	18A28	18A24	18A25	18A26	18A27	19A2	19A3	Series Means	Grand Means
Quartz	a	26.6	29.2	29.2	27.1	28.9	27.9	26.8	25.6	27.7	26.8	30.0	27.8	
	b	26.4	27.4	27.0	28.2	29.7	27.2	27.9	26.2	26.4	27.1	30.5	27.6	27.8
	c	27.6	26.8	28.4	28.1	28.7	29.2	27.3	23.8	27.6	26.5	32.0	27.8	
Orthoclase	a	32.4	32.0	30.3	32.3	29.4	34.3	30.9	36.2	35.5	*	29.5	32.3	
	b	33.4	33.6	34.2	32.1	32.0	31.9	31.9	35.7	38.1	37.4	31.2	33.8	32.9
	c	33.5	34.4	32.9	29.9	30.5	32.2	31.8	33.3	36.6	36.3	26.2	32.5	
Plagioclase	a	34.6	32.2	32.5	33.7	32.5	29.0	34.2	31.7	32.2	*	34.6	32.7	
	b	33.7	32.2	31.9	33.2	31.2	33.5	34.1	31.7	30.7	30.8	33.5	32.4	32.7
	c	33.1	31.7	30.5	33.8	33.1	31.0	33.4	37.7	31.0	31.4	36.1	33.0	
Biotite	a	4.2	3.6	4.3	3.4	3.4	2.6	3.9	2.9	2.9	3.0	2.1	3.3	
	b	5.1	3.9	3.5	3.8	3.8	3.5	3.9	4.7	2.9	4.1	2.5	3.9	3.7
	c	4.4	3.8	4.1	5.2	4.3	3.2	4.4	3.8	2.9	4.1	3.3	4.0	
Muscovite	a	1.2	2.4	2.7	1.8	4.7	4.9	2.9	2.2	0.8	1.5	2.3	2.5	
	b	0.6	1.7	2.1	1.4	2.1	3.0	1.6	0.6	0.9	0.5	1.7	1.5	1.9
	c	0.6	2.6	3.1	1.9	2.4	3.6	1.7	0.8	1.0	0.7	1.9	1.8	
Opaque	a	0.9	0.4	0.7	1.4	0.8	1.0	1.2	1.0	0.8	†	0.3	0.8	
	b	0.6	0.7	0.8	1.1	0.8	0.4	0.4	0.9	0.7	0.5	0.4	0.7	0.7
	c	0.8	0.6	0.6	1.0	0.7	0.7	1.1	0.4	0.8	0.7	0.3	0.8	
Others	a	0.1	0.2	0.3	0.3	0.3	0.3	0.1	0.4	0.1	†	1.2	0.3	
	b	0.2	0.5	0.5	0.2	0.4	0.5	0.2	0.2	0.3	0.1	0.2	0.3	0.3
	c	0.0	0.1	0.4	0.1	0.3	0.1	0.3	0.2	0.1	0.3	0.2	0.2	

Bradford Mineral	Series	Spec. No. 19A5	19A6	19A7	19A8	1911	Series Means	Grand Means
Quartz	a	22.9	28.4	24.5	24.4	22.6	23.6	
	b	22.4	22.7	23.7	21.9	24.2	23.0	23.2
	c	22.9	21.1	22.5	24.5	23.8	23.0	
Orthoclase	a	27.9	27.6	24.7	26.0	26.3	26.5	
	b	26.5	25.9	27.0	29.4	26.6	27.1	27.1
	c	27.2	26.8	27.6	27.1	29.2	27.6	
Plagioclase	a	38.2	41.0	39.9	40.2	41.6	40.1	
	b	41.5	41.8	41.1	38.5	39.2	40.4	40.6
	c	42.1	42.8	40.1	41.7	40.0	41.3	
Biotite	a	7.3	6.1	6.9	6.1	7.1	6.7	
	b	6.7	7.6	5.6	7.0	7.2	6.8	6.4
	c	4.7	7.8	6.3	5.0	4.5	5.7	
Muscovite	a	2.0	0.4	2.4	2.3	1.3	1.7	
	b	1.4	0.9	1.4	1.4	1.6	1.3	1.4
	c	1.9	0.3	1.6	0.9	1.6	1.2	
Opaque	a	0.8	0.6	0.5	0.5	0.5	0.6	
	b	0.5	0.8	0.6	1.1	0.9	0.8	0.7
	c	0.8	0.5	0.6	0.4	0.6	0.6	
Others	a	0.9	0.9	1.1	0.5	0.6	0.8	
	b	1.0	0.3	0.6	0.6	0.3	0.6	0.7
	c	0.4	0.7	1.3	0.4	0.3	0.6	

* Not measured separately: Total Feldspar = 68.1
† Not measured separately: Total Accessories = 0.6

Identification of Specimens

Westerly:

18A18	Chapman Quarry, "gray"
18A19	Chapman Quarry, "pink-gray"
18A20	Smith North Quarry
18A21	Small opening between Smith North and Frazer
18A23	Dixon Quarry
18A24	Calder-Carnie Quarry, "pink"
18A25	Calder-Carnie Quarry, "gray"
18A26	Catto Quarry, medium grained (fine according to Dale)
18A27	Present Smith Quarry, "light pink"
19A1	Present Smith Quarry ("Smith new east" of Dale)
19A2	Present Smith Quarry, near dressing shed, "light pink"
19A3	Same as 19A2, "blue"

Bradford:

19A5	Sullivan Granite "Mine"
19A6	W. end of first Quarry E. of 19A5 (Newall?)
19A7	E. end of Newall (?) Quarry
19A8	Klondike Quarry
19A11	Easternmost Quarry of Sullivan group

chlorite may be primary, but for the most part its origin by replacement of biotite is obvious. Chlorite is on the whole a very minor constituent and even in those slides in which it is most abundant the bulk of the biotite is unaffected; it has been recorded with biotite in the analyses.

As in most of the finer-grained granites of New England, plagioclase tends to be euhedral or at least subhedral, while potash feldspar characteristically forms incomplete coatings about it, is mostly quite anhedral, and sometimes poikilitically encloses not only plagioclase but quartz and biotite as well. This relation between the feldspars is brought out sharply by the sodium-cobalti-nitrite stain to which all of the slides were subjected before analysis. The potash feldspar of both Westerly and Bradford is usually microcline but twinning is rarely sharp and in some grains is not found at all.

A hand specimen was taken from each of the larger quarries at Westerly and Bradford. In a few cases two or more specimens were taken at widely distant points in the same working; from some of the smaller quarries no collection was made. From each hand specimen, as has already been explained, three thin sections were cut: two of these being parallel and as close together as possible, the third inclined and as far as possible from the first pair. Analytical results are shown in table 1; *a* and *b* are the closely spaced pair. The *a* series was cut and analyzed nearly a year before the other two; the *b* and *c* series were all run within a week of each other. Thus a comparison of *a* and *b* with *c* is some measure of differences within hand specimens, while loss of control in the analytical procedure may be detected by comparing *b* with *a*. It turns out in fact that neither effect is large enough to cause concern, so that the three sections may be regarded as random samples for all the major constituents.

C. EXAMINATION OF ANALYTICAL RESULTS:

VARIANCE ANALYSIS OF WESTERLY BIOTITE VALUES

At this point it is necessary to introduce a method and approach still novel in petrology though widely used in agricultural sciences. The method is the analysis of variance, and the interested reader will find an excellent non-mathematical treatment of the procedures used here in chapters 10 and

15 of Snedecor (1946). A paper on descriptive petrography suffers quite as much from the insertion of expositions of statistics as it does from an excess of thermodynamic speculation. Still, the application of variance analysis to the data of table 1 is easily the most important part of this paper. Rather than present the reader with a number of arbitrary conclusions based on a series of incomprehensible tables I shall first describe briefly the objectives of the procedure and then go through it step by step with the Westerly biotite values shown in the table. I hope this will make the results more meaningful to the general reader but strongly urge that the petrographer interested in applying the method to his own data consult a primary reference before doing so, and preferably before taking his sample.

The use of the standard deviation as an index of dispersion of measurements about their mean is familiar to everyone. The standard deviation is defined as

$$s = \left(\frac{\overset{n}{\underset{i=1}{S}} (X_i - \bar{x})^2}{n-1} \right)^{\frac{1}{2}}$$

where $\bar{x}$ is the mean of X_1, X_2, ---X_i---X_n measurements. Now a single standard deviation may be and usually is the resultant of many sources of variations in the data; and, although it is a satisfactory measure of total dispersion, it does not permit ready isolation of contributions to this variability arising from separate sources. In variance analysis basic computations are made not with the standard deviation, s, but with the quantity $(n-1)s^2$, or $\overset{n}{\underset{i=1}{S}}(X_i - \bar{x})^2$, the sum of squares of deviations of measurements about their mean, for it may be shown that the separate sources of variability in *any* set of data contribute additively to this "sum of squares." From the total sum of squares for the entire group of measurements the amount contributed by each known source, computed in similar fashion, is subtracted off. Just as the divisor (n-1) reduces the total sum of squares to a mean square, or variance, for the entire batch of data, suitable divisors, obtained in comparable fashion, reduce each partial sum of squares to a mean square or variance arising from each

source of variation. The divisor is in each case the degrees of freedom allotted to the source in question, a degree of freedom being the number of items less the number of linear constraints involved. (Where there are n items, for instance, and the sum of squares is computed from the sample mean, only (n–1) of the items are independent, for $X_n = n\bar{x} - \underset{i=1}{\overset{n-1}{S}} (X_i)$, and $(X_n - \bar{x}) = \underset{i=1}{\overset{n-1}{S}} (\bar{x} - X_i)$. There are therefore (n–1) degrees of freedom.) There remain finally a series of mean squares, each estimating a sum of squares per degree of freedom arising from a single source or a combination of (known) sources. Comparison of these variances in the fashion prescribed by the experimental design is the final step of the analysis. The distribution of sample estimates of the variance ratio for *equal* parent variances is used as the model. If the sample estimate is large enough to be unlikely, the hypothesis that the parent variances are identical is discarded. In our case, for instance, if the ratio

$$F = \frac{\text{sample variance}}{\text{sub-sample variance}} = \frac{\text{variance of means of hand specimens}}{\text{variance within hand specimens}}$$

were suitably large, the conclusion would be that differences between hand specimens were large enough to be detected and estimated by the experimental procedure.

Biotite values for the Westerly thin sections are shown in table 2 arranged to facilitate the computations.

TABLE 2

BIOTITE VALUES OF WESTERLY THIN SECTIONS, FROM TABLE 1

	Series	*a*	*b*	*c*	Sums for hand specimens
Spec.	18A18	4.2	5.1	4.4	13.7
	18A19	3.6	3.9	3.8	11.3
	18A20	4.3	3.5	4.1	11.9
	18A21	3.4	3.8	5.2	12.4
	18A23	3.4	3.8	4.3	11.5
	18A24	2.6	3.5	3.2	9.3
	18A25	3.9	3.9	4.4	12.2
	18A26	2.9	4.7	3.8	11.4
	18A27	2.9	2.9	2.9	8.7
	19A2	3.0	4.1	4.1	11.2
	19A3	2.1	2.5	3.3	7.9
				(Grand Total)	121.5

The first step is to compute the total sum of squares. Denoting by x a deviation, by $\bar{x}$ a mean, and by X a measurement,

$$\bar{x} + x_1 = X_1.$$

Squaring both sides, summing, and converting $n\bar{x}^2$ to $\frac{[S(X)]^2}{n}$ gives $S(x^2) = S(X_1 - \bar{x})^2 = S(X_1^2) - \frac{[S(X)]^2}{n}$. Thus the total sum of squares is given by $(4.2)^2 + (5.1)^2 + \ldots + (3.3)^2 - \frac{(121.5)^2}{n} = 16.729$. If the experimental design did not permit isolation of separate sources of variability (if, for instance, all thin sections were cut from a single hand specimen or each thin section from a different hand specimen), the variance for the entire array would be obtained next as

$$16.729/32 = 0.5228,$$

the standard deviation would be simply the square root of the variance, or 0.723, and this would be the end of the trail. Having designed the experiment to permit isolation of distinct sources of variation, however, we are not entitled to make such a computation until and unless we find reason for supposing that each source contributes similarly to the total variance; *e.g.*, that the data appear homogeneous. The hypothesis of homogeneity is tested by comparing the sample estimates of variance with each other, so that the next step is to compute these values from the sample.

The sum of squares for differences between hand specimens may be reached in either of two ways. An average value for each hand specimen may be obtained from the *a*, *b*, and *c* values in the appropriate row, and the sum of squares of these averages about the grand mean computed exactly as for the total sum of squares. If a computing machine is available, and sometimes if it is not, an identical result will be obtained in less time by working with the sums rather than the averages, thus

$$\frac{(13.7)^2 + (11.3)^2 + \ldots + (7.9)^2}{3} - \frac{(121.5)^2}{33} = 9.9358.$$

We have used the grand mean as the origin of the deviations of the hand specimen means so only 10 of the 11 hand specimen means are independent, and the mean square or variance for hand specimens is given by $9.9358/10 = 0.9936$.

In the conventional analysis of variance both row and column classifications are completely exclusive, and a sum of squares and mean square for column means is computed just

as for row means. If the *a*, *b*, and *c* sections had been cut, respectively, in the planes of rift, grain, and hardway, for instance, this comparison might be useful, and an orientation examination of this sort would certainly be desirable for work on schists and gneisses. In our case, however, though the assignment of slides to rows is sharp and clearcut, their assignment to columns is rather arbitrary. If all the sawing had been done at one time, as would usually occur, the *a* and *b* values would be completely interchangeable, there would be 2^{11} or 2048 ways in which the *a* and *b* columns could be arranged, and no one pair of column means would be more meaningful than any other. Similarly, the assignment of one of two distant slides to *c* is just a question of where the *b* slide is taken. Thus it is not the differences between column means that concern us but the *differences between entries in each row.* The difference $(a–b)$ is an indication of how closely a slide may be duplicated and the difference $[(a+b)/2]-c$ is an indication of how widely composition may vary in the hand specimen. The sum of squares for "duplication" is given by $\frac{1}{2}[S(a–b)^2]$ which in this case comes to 3.640; the sum of squares for variability within hand specimens, or "replication," is $\frac{2}{3}[S\left(\frac{a+b}{2}-c\right)^2]$ or 3.153. Each sum of squares is generated by 11 independent differences, so the appropriate mean squares are $3.640/11 = 0.3309$ and $3.153/11 = 0.2866$.[2]

Assembling the results in tabular form gives:

Source of Variation	*Sum of squares*	*Deg. of freedom*	*Mean square*
Between hand Specimens	9.936	10	0.9936
Within hand specimens			
Replication $\left(\frac{a+b}{2}-c\right)$..........	3.153	11	0.2866
Duplication $(a-b)$	3.640	11	0.3309
	16.729		

The operations performed so far are purely algebraic; a total sum of squares may be partitioned in similar fashion for

[2] Though replication refers strictly to *any* repetition, in agricultural experimentation it usually applies to repetitions of treatments under different conditions. Regarding preparation and analysis of a thin section as "treatment" and distance between thin sections on the same hand specimen as "difference of condition," any two thin sections cut from the same hand specimen are replicates, and a duplicate is a special case of replication in which the difference of condition has been as nearly as possible eliminated. Reasoning behind the rather arbitrary formulas for the within specimen sums of squares is given in Appendix A.

any body of multiple-classified data just as a sum of squares, a mean square, and a standard deviation may be computed for any singly classified list of numbers. In both cases degrees of freedom are determined by the pattern of the classification so that variances, whether representing total or partitioned sums of squares, may be regarded solely—and sometimes quite usefully—as sample descriptions.

The main object of variance analysis, however, is not to describe a sample but to reach inferences about the parent population from which the sample is drawn. It helps some to know, for instance, that the between specimen mean square is larger than the mean square for duplication; but what we would really like to know is whether the difference is large enough so that we may reasonably infer a source of inter-hand specimen variability over and above the error of duplication. Now the actual test of the variances does involve certain assumptions not involved in their computation. Chief among these is the requirement that the parent variation of each source be normally or "sufficiently normally" distributed. In practice, considerable departures from normality may be tolerated; a .01 probability for a truly normal distribution may be a .005 or .02 probability for a moderately skewed or otherwise non-normal distribution, but as we conclude in any case merely that the event giving rise to it is sufficiently rare to require explanation, the difference is often not material.

Probability inferences are of course valid only for unbiased measurements of randomly chosen samples. I know no reason to suspect significant bias in analytical procedure except in the case of muscovite in the Westerly granite, of which more will be said below. The hand specimens were taken without regard for orientation, position in the rock body, or proximity of country rock and inclusions; their variation thus includes but does not permit isolation of contributions made by systematic gradients in composition in the masses from which they come. I believe that in most of the granites of New England variations of this type are of minor significance and are, in general, so slight that even their detection would require a considerable amount of work.[3]

[3] For a very different view of the situation, based on a study of the Bradford granite, see A. Quinn, Am. Mineralogist, vol. 28, pp. 272-281, 1943. The mean values for major constituents in the Bradford granite given here agree remarkably with those obtained earlier by Dr. Quinn, but his individual analyses show a much wider range.

It seems to me we have ample justification and precedent for applying variance analysis to studies of the composition of rocks, providing we do so skeptically and with reasonable caution. The conclusion of the analysis already used as an example is simple and straightforward.

The ratio of replication mean square to duplication mean square is $F = 0.2866/0.3309 = 0.8661$, which clearly offers no reason to suppose that variations within hand specimens are large enough to require special explanation. In fact, barring the emergence of an F at least as large as 2.82 and preferably as large as 4.46 (Snedecor, 1946, pp. 222-225 and discussion), we must conclude that the location of thin sections in the hand specimens is without detectable effect on the result. We may therefore regard the a, b and c sections as random samples of each hand specimen and pool the variances arising from duplication and replication into a single mean square for "within-hand specimens" or "experimental error." Since the sums of squares and degrees of freedom are additive, this operation amounts only to

	Sum of squares	*Deg. of freedom*	*Mean square*
Replication $\left(\frac{a+b}{2}-c\right)$	3.153	11	
Duplication $(a-b)$	3.640	11	
Experimental error	6.793	22	0.3088

The final analysis of variance is thus

Source	*Sum of squares*	*Deg. of freedom*	*Mean square*
Between-hand specimen	9.936	10	0.9936
Experimental error	6.793	22	0.3088

$$F = 0.9936/0.3088 = 3.22^{*}$$

As the .05 and .01 points for F bracket the sample value (.05 = 2.30, .01 = 3.26), there is a strong but perhaps not completely convincing suggestion that differences between hand specimens are greater than experimental error. Interpretation of a borderline case like this is always to some extent a matter of judgment. If $F = 3.22$ is regarded as significantly large, then the standard deviation of 0.723 for the entire group, computed at the opening of this section, must be replaced by two new calculations.

For variations between hand specimens after extraction of experimental error we have

$$\sqrt{\frac{0.9936 - 0.3088}{3}} = 0.48\%$$

and for experimental error, the combination of within-hand specimen variation and analytical error, $\sqrt{0.3088} = 0.56\%$. Now from the relation set up (Chayes, 1949a), the analytical error itself—that is, the reproducibility of a result *on the same thin section*—would be estimated at between 0.47 and 0.53 per cent, depending on count length, so that whether we are thinking of analytical error, experimental error, or differences between hand specimens the overall standard deviation computed without partition of the total sum of squares seems misleading. In this particular case the difference between total and hand specimen or error variances is not large; in other cases it might be much larger.

D. EXAMINATION OF RESULTS: INFLUENCE OF TIME OF ANALYSIS ON PRECISION

It has been mentioned that the *a* slides were cut and analyzed several months before the *b* and *c* series. Since all of the analyses were run during a time when the method itself was in the process of development, the possible effect of time of analysis on the caliber of the results is a matter of considerable interest. For the purpose of this experiment, of course, a time effect is of paramount importance quite aside from methodology, for if it is substantial the use of *a* on common footing with *b* or *c* is immediately suspect, and comparisons between hand specimens must be carried through with only two instead of three slides per specimen, weakening the test proportionately.

Though there is no way in which a pure time factor may be drawn from the results, the expected analytical error may be computed from the appropriate binomial (Chayes, 1949a); and, if the observed differences between *a* and *b* are not larger than might occur from analytical error alone, it may be safely concluded that variation introduced by the time lapse between analyses (plus whatever slight differences there may be between adjacent thin sections) is small enough to be neglected. This is not to say either that there is no time effect or that adjacent sections are identical, but only that variation from the com-

bined effect of these two sources is too small to be detected with the present analytical error and experimental design.

The theoretical analytical error or *reproducibility of results for a single thin section* is given by

$$\sigma_1 = 100 \sqrt{\frac{p(1-p)}{n}}$$

where p is the amount of constituent X_1, n is the count length, and σ_1, is in terms of parts per hundred of the whole.

In practice, of course, we do not know p, but use $\bar{x}$ as an approximation; this is satisfactory so long as the range of composition of thin sections is small, for σ is not very sensitive to small differences in p. Similarly, an average value may be used for n; n was taken equal to 1400 in the calculations below, though none of the inferences reached would have been different for n as small as 1300 or as large as 1500.

If *a* and *b* were actually duplicate analyses of the same thin section, the sample statistic to be compared with σ_1 would be

$$s_1 = \sqrt{\frac{1}{2t}\overset{t}{\underset{1}{S}}(a_i - b_i)^2}.$$

The variance ratio table used in the preceding section also provides a convenient test of the relation between s_1 and σ_1. It is necessary only to compute

$$F = \frac{s_1^2}{\sigma_1^2}$$

and compare this with the tabled value of F^k_∞ where k is the number of differences available for the computation of s_1. σ is presumed to be known exactly which would be the case if it had been determined from an infinite number of differences. Results of the computation for the *a* and *b* series of table 1 are shown below in table 3.

TABLE 3

COMPARISON OF DIFFERENCES BETWEEN *a* and *b* (TABLE 1) WITH EXPECTED ANALYTICAL ERROR

Granite	*Mineral*	s^2	σ^2	F
Westerly	Quartz	0.639	1.430	0.45
	Orthoclase	2.112	1.580	1.34
	Plagioclase	1.342	1.568	0.86
	Biotite	0.331	0.248	1.33
	Muscovite	0.784	0.140	5.64**

Bradford Quartz	1.019	1.274	0.80
Orthoclase	2.179	1.406	1.55
Plagioclase	2.162	1.727	1.25
Biotite	0.512	0.441	1.16
Muscovite	0.251	0.324	0.77

$$(.05 \text{ points, } F^{11}_{\infty} = 1.79,\ F^{10}_{\infty} = 1.88,\ F^{5}_{\infty} = 2.21;\ .01 \text{ point, } F^{11}_{\infty} = 2.24)$$

Except for Westerly muscovite all the F values of table 3 fall far short of significance. This is a most encouraging result, not only for its general implication but in the specific sense that the design of the experiment may be maintained for 85 per cent of the observations and nine of the ten comparisons originally planned.

I believe there is a reasonable explanation for the difficulty with Westerly muscovite, and that consistent and reliable results may be obtained for fine-grained constituents by the use of two simple precautions not required where grains are large. As this is a matter of technique and will interest only those actually concerned with using the point counter, discussion of it has been placed in an appendix.

Measurements of all five essential constituents in Bradford and of four of the five in Westerly, seem to be free of any detectable time effect. In all these cases we are free to regard the three measurements of each hand specimen as directly comparable, so that differences between them or their means in any valid arrangement reflect true sampling variation rather than erratic or systematic differences in analytical error. For the Westerly muscovite, the *a* series of measurements must be eliminated from further calculations and the comparison between hand specimens carried through with only two thin sections per specimen.

E. EXAMINATION OF RESULTS: VARIATIONS WITHIN AND BETWEEN HAND SPECIMENS

The preceding section having failed to cast suspicion on the homogeneity of the data of table 1 as far as analytical technique is concerned (except, of course, for Westerly muscovite), the remainder of the variance analysis follows exactly the pattern of the sample calculation of section C. Mean squares for the two within-specimen sources of variation are shown in table 4.

TABLE 4

SUBDIVISION OF WITHIN-SPECIMEN VARIATION
LOCATION OF THIN SECTION IN HAND

Rock	Mineral	Deg. of freedom	Mean square duplication $(a-b)$	re[illegible] $\left(\frac{a+}{2}\right.$
Westerly	Quartz	11	0.639	[illegible]
	Orthoclase	10	2.112	[illegible]
	Plagioclase	10	1.342	[illegible]
	Biotite	11	0.331	[illegible]
Bradford	Quartz	5	1.019	[illegible]
	Orthoclase	5	2.179	[illegible]
	Plagioclase	5	2.162	[illegible]
	Biotite	5	0.512	[illegible]
	Muscovite	5	0.251	[illegible]

(.05 points for F; $F^{11}_{11} = 2.82$, F^{10}_{10} :
$F^{5}_{5} = 5.05$)

In no case does the ratio

$$\frac{\text{mean square for replication}}{\text{mean square for duplication}}$$

exceed the appropriate .05 point of F, and
Bradford biotite and Westerly plagioclase do
approach this value. There is thus no evid
within hand specimens over and above tha
duplication, and, as we have already seen,
variance itself is not significantly larger than
tered in multiple analyses of the same thin s
might the thin sections have been taken anyw
specimens, but apparently a comparable resul
reached had each set of three analyses been c
thin section.

Since within-specimen differences are negli
differences between hand specimens is greatly
pooling all internal variation into a single
experimental error, as described in section C
calculation are shown in table 5, only b and c
for the computation of Westerly muscovite m

In Bradford only muscovite seems to v
between hand specimens while in Westerly only
to do so. Now F may fail of significance e
numerator is small or its denominator large. A

TABLE 5

EXPERIMENTAL ERROR AND BETWEEN-SPECIMEN MEAN SQUARES
(Westerly Muscovite Values Based on *b* and *c* Only)

Rock	*Mineral*	*Experimental error df*	*mean square*	*Between specimen df*	*mean square*	*F*
Westerly	Quartz	22	0.768	10	6.085	7.92**
	Orthoclase	20	2.187	9	14.528	6.64**
	Plagioclase	20	2.236	9	4.832	2.16
	Biotite	22	0.309	10	0.995	3.22*
	Muscovite	11	0.120	10	1.571	13.09**
Bradford	Quartz	10	1.070	4	0.943	0.88
	Orthoclase	10	1.822	4	0.589	0.32
	Plagioclase	10	1.939	4	1.482	0.76
	Biotite	10	1.277	4	0.589	0.46
	Muscovite	10	0.204	4	0.802	3.93*

* suggestive variance ratio
** highly significant variance ratio

between error mean squares for major constituents are trifling, there is a clear implication that Bradford is a considerably more homogeneous granite than Westerly, in the sense that composition differences between hand specimens are smaller. This is a rather unexpected result but concurrent inspection of hand specimens, field notes, and the results shown in table 1 persuades me that the wider range of composition of Westerly is not to be traced to specimens which might have been excluded from the sample on the basis of appearance or field relations.

It remains only to estimate, again following the procedure of section C, the between-specimen variance components for those constituents for which its significance is suggested or established; namely, Bradford muscovite and all Westerly minerals save plagioclase. These estimates together with corresponding standard deviations and 4s intervals are shown in table 6.

TABLE 6

VARIANCE COMPONENTS, STANDARD DEVIATIONS, AND 4S INTERVALS FOR BETWEEN-SPECIMEN DIFFERENCES

Mineral		*Variance component*	*s, per cent of whole*	*4s interval*
Westerly	Quartz	1.77	1.33	5.32
	Orthoclase	4.11	2.03	8.12
	Biotite	0.23	0.48	1.92
	Muscovite	0.72	0.85	3.40
Bradford	Muscovite	0.20	0.45	1.80

It would be possible to define a homogeneous rock as one in which between-hand specimen differences were not significantly

larger than experimental error, and on this basis Bradford would be homogeneous while Westerly would not. On the other hand, the experimental error will vary not only with the analytical method but with design of the experiment, and there seems to be very little need, at least at present, for an all-or-none characterization of homogeneity. The Westerly is apparently more variable in composition than the Bradford, but an estimate of its range of variation from hand specimen to hand specimen, as shown in the last column of table 6, is much more useful than a qualitative classification.

F. VARIABILITY OF THE FINER-GRAINED GRANITES OF NEW ENGLAND

The reader will have guessed that this study has not been carried on *in vacuo*. Although complete results for the much broader examination of which it is a part are not yet ready for publication, sufficient information has been accumulated to indicate that the variability of most of the finer-grained granites of New England is of the same general order as that shown by Westerly and Bradford.

For the remainder of my collection, consisting of hand specimens taken in about the same fashion as at Westerly and Bradford, only a single thin section has so far been cut from each specimen. The variance for each district is thus analogous to that shown by either the *a*, *b*, or *c* series of table 1, and is to be regarded as an estimate of the variation in composition of areas of three-quarters square inch (*not* hand specimens). As an illustration of the general trend of the results the variance analysis for quartz is shown in table 7.

TABLE 7

VARIANCE ANALYSIS FOR QUARTZ, FINER-GRAINED CALC-ALKALINE GRANITES OF NEW ENGLAND

Source of Variation	*Degrees of Freedom*	*Mean Square*
Between districts	17	53.847
Within districts	127	4.554

$$F = \frac{53.847}{4.554} = 11.82^{**}$$

It is evident that there are highly significant differences between districts but the analysis does not tell whether these are in the means, the variances, or both. Ordinarily, as in the pre-

ceding sections, the experiment is so designed that the assumption of homogeneous variance within sub-groups is permissible. Here, however, where differences in composition, grain size, mixing, etc., are involved, this assumption is not justified in advance and must be tested against the data. The test (see Snedecor, 1946, p. 251) has been performed on the measurements from which table 7 has been computed, but a full description of it would carry the discussion too far afield. It will be much more useful to list the relevant data and discuss them qualitatively. Material for the discussion is contained in table 8.

TABLE 8

MEANS AND STANDARD DEVIATIONS FOR QUARTZ

(Data of Table 7)

State and district	*Number of specimens*	*Mean*	*Standard deviation*
Rhode Island			
Westerly	11	27.7	1.31
Bradford	5	23.1	1.08
Massachusetts			
Westwood	8	30.6	1.70
New Hampshire			
Concord	7	30.8	2.72
Milford	13	26.9	2.44
Fitzwilliam	14	31.0	1.92
Vermont			
Barre	22	27.0	2.54
Woodbury	8	26.5	2.91
Maine			
Pownal	14	28.8	1.46
Swanville	4	25.5	0.74
Clark Island	14	33.2	2.62
North Sullivan	10	32.3	1.89
Hallowell	5	31.0	0.94

(Districts represented by less than four specimens are omitted)

The test fails to establish any heterogeneity of variance, though it is possible that if certain districts (Concord, Woodbury, and Swanville, for instance) were better represented the case might be otherwise. Geologists familiar with these granites will note that for all the comparatively coarse rocks s in table 8 is 1.89 or larger, while for the finer-grained members $s \leqslant 1.70$.

However this may be, there is, on the whole, astonishingly little variation in quartz content within each district and on the basis of over 140 thin sections from 15 of the major quarrying areas of New England it cannot be shown that the amount

of this variation differs significantly from area to area. The evidence indicates that the quartz content of two randomly chosen thin sections from any one of these areas would very rarely differ by as much as nine per cent, and would usually be in far better agreement than this. From the results for Bradford and Westerly it would seem to matter little whether the sections were taken from a single hand specimen or from widely separated localities in a given granite body.

The importance of this conclusion is obvious when one considers that of the two dominant hypotheses of granite formation one suggests the formation of granitic liquid from basaltic by crystal fractionation and the other has granites formed by the reaction of something or other with sediments. Positive petrographic evidence that a particular granite body formed by either process would seem to demand a much broader range in composition than has been or is likely to be found in most granite bodies.

Exponents of the crystal fractionation hypothesis may avoid this dilemma by supposing that fractionation normally occurs at depth, so that granite magmas are mostly prefabricated by the time they make their entry into the now visible portions of the crust. This brings the hypothesis into accord with what seem to me to be the facts, but it can hardly be regarded as strong evidence for the hypothesis.

The strength of the various "transformist" hypotheses, however, is that they allegedly require no such sleight of hand, but are able to explain the formation of granite by gradual and progressive alteration of sediments in the visible portions of the crust. For the vast bulk of New England calc-alkaline granite these hypotheses are elaborate conceits designed to explain variations which either do not exist at all or occur only on a scale so slight that they cannot reasonably be regarded as of regional importance.

I am aware that this conclusion will be unpopular in the extreme, and that the advocate of one or other ultrametamorphic process can now cite a virtually endless list of works by fellow devotees supporting his view of the situation. Considering the remarkable disregard for the most elementary principles of sampling that characterizes most work on variations in rock composition (whether by magmatists or migmatists), it is only a mild exaggeration to say that present views of the subject bear about the same relation to the actual state of

affairs as public opinion polls did to the last presidential election. From present indications intra-granite variations in composition will generally be so small that their estimation, and sometimes even their detection, will usually require persistent quantitative study of properly chosen samples far larger than are now customarily used.

Whether or not fractionation may have occurred at depth I do not pretend to know, but in the portion of the Earth's crust usually exposed for study—or at least that portion of it so exposed in New England—there is rarely any evidence that granite has been derived either from basaltic magma or sialic sediments. It simply is, and it would be most simply explained as the crystallized equivalent of a liquid not very different in composition from the visible rock.

G. SUMMARY

A rather detailed study of small samples of the granites of Westerly and Bradford, Rhode Island, indicates that these granites are remarkably homogeneous in composition. Hand specimens of the Westerly granite apparently do vary in composition but the amount of variation is very small. Differences between hand specimens of the Bradford granite could not be reliably detected.

Similar but less detailed studies of small samples of most of the finer-grained calc-alkaline granites of New England suggest that these results are not atypical. Evidence is presented indicating that the range of quartz content of thin sections from any one of these granites will rarely be as much as nine per cent, and that commonly it will be a good deal less. A more complete study dealing with variations in each of the major constituents will be published in the near future.

Hypotheses of granite formation requiring or implying extensive variations in composition within granite masses are rendered suspect by evidence that such variations either do not exist or are very rare. The simplest explanation for the existence of vast masses of material so nearly uniform in composition would be their formation by crystallization from a magma of approximately the same composition. Concerning the origin of these parent magmas, the rocks themselves provide very little information. If they form by crystal fractionation of a basaltic magma, the process must be a very deep-seated one, for in most cases—including all reported on here—systematic

tendencies toward concurrent depletion in quartz, enrichment in dark silicates, and in anorthite content of plagioclase are lacking. On the other hand, variants extremely rich in quartz or muscovite, such as would be expected if granites formed by transformation of sediments, are also entirely lacking in the sample and must be extraordinarily rare in the rocks.

H. ACKNOWLEDGMENTS

I am deeply indebted to J. M. Cameron and W. J. Youden of the Statistical Engineering Laboratory of the National Bureau of Standards, both of whom have been generous of their time and tolerant of my ignorance. The novice, and particularly the novice unskilled in mathematics, is usually obliged to force his data into one of the type patterns of variance analysis so well described in textbooks designed for students of the biological sciences. This is exactly what I had done when I first discussed the work with Mr. Cameron. In this case the within-specimen variance is so small that almost any legitimate treatment of it will suggest the use of a pooled variance or total experimental error for the final comparisons, so that the major results of my cookbook approach were identical with those given here. But the interpretation of within-specimen variance had only a trivial physical meaning and the treatment of time effect not only appeared as something of an afterthought but did not clearly separate the effects of time from those of location. In the present organization of the analysis I believe every computation has a simple and important physical meaning which will be apparent to anyone seriously interested in the problem: the extent to which this is true is a reflection of the amount of advice and assistance I have received from Mr. Cameron and Dr. Youden.

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Appendix A

COMPUTATION OF SUMS OF SQUARES FOR DUPLICATION AND REPLICATION

1. *Sum of squares for duplication.* If $x = (a+b)/2$, and ϵ is the difference between either value and the mean of the pair, then the desired sum of squares is

$$S(d_1^2) = S(\epsilon_\alpha^2) + S(\epsilon_\beta^2) = 2S(\epsilon_\alpha^2)$$

for obviously $\epsilon_\alpha = -\epsilon_\beta$. Now

$$\epsilon_\alpha = a - \bar{x} = \frac{a-b}{2}$$

and
$$S(\epsilon_\alpha^2) = S\left(\frac{a-b}{2}\right)^2 = \tfrac{1}{4}S(a-b)^2.$$

Hence
$$S(d_1^2) = 2S(\epsilon_\alpha^2) = \tfrac{1}{2}S(a-b)^2$$

which is the quantity used in the calculation on page 21.

2. *Sum of squares for replication.* There ought to be an analogous algebraic identity to cover this case but I have so far been unable to find it. However, the calculation may be made to appear reasonable in the following fashion.

The total sum of squares available for partition is

$$\underset{x=a}{\overset{c}{S}}\ \underset{i=1}{\overset{11}{S}}\ (X_i^2) - n\bar{\bar{x}}^2.$$

Variations between hand specimens take up $\tfrac{1}{3}S(a+b+c)^2 - n\bar{\bar{x}}^2$ of this, and failure of duplicates to agree exactly consumes $\tfrac{1}{2}S(a-b)^2$. Anyone who cares to perform the necessary drudgery will find that

$$\underset{x=a}{\overset{c}{S}}\ \underset{i=1}{\overset{11}{S}}\ (X_i^2) - \tfrac{1}{3}S(a+b+c)^2 - \tfrac{1}{2}S(a-b)^2$$
$$= \tfrac{1}{6}S(a^2+b^2+2ab+4c^2-4ac-4bc)$$

which reduces to $\tfrac{1}{6}S(a+b-2c)^2$.

After extraction of contributions made by other sources, the sum of squares available for replication is thus

$$S(d_2^2) = \tfrac{1}{6}S(a+b-2c)^2 = \tfrac{2}{3}S\left(\frac{a+b}{2} - c\right)^2,$$

this last form being used in the computation on page 21 in order to indicate that the replication sum of squares reflects the failure of c to agree exactly with the mean of a and b.

If a computing machine is available, it is much quicker to cumulate the sum of the $(a+b-2c)^2$ term and divide by six.

Appendix B

Notes on the Difficulty of Obtaining Consistent Estimates of Fine-Grained Constituents

The discrepancies between the *a* and *b* values for Westerly muscovite are quite extreme, the observed variance ratio being more than twice as large as the .01 point of the appropriate F; but until I had carefully reviewed my laboratory notes, with particular attention to the dates at which various studies were made, I could find no reasonable explanation of the difficulty. Much of the Westerly muscovite occurs as minute specks scattered through plagioclase and it is in the treatment of these that the *a* and *b* series differ. Wide and erratic differences in estimates of constituents whose grain areas are frequently of about the same order as the area of the cross-hair intersection are one of the major problems of this type of microscopy, so a review of my experience with the matter may be helpful to others. The sequence of events I believe responsible for the instability of the Westerly muscovite values was about as follows.

Slides of the Westerly and Barre granites were part of the set run in duplicate for the original precision test of the point counter, when I had no idea that useful results could be obtained so easily for minor constituents or for very fine-grained ones. Next I etched and stained all the granite slides in my collection, to eliminate the sometimes bothersome and time-consuming business of distinguishing plagioclase from potash feldspar during analysis, and proceeded to reanalyze the entire collection beginning with what are here recorded as the *a* series of Westerly.

By this time the consistency of results for major constituents was pretty well established and the results for minor ones seemed so promising that I began a detailed study of the plagioclase-sericite relation in the Barre granite, which is relatively rich in muscovite. In work of this sort it is customary to operate with the microscope slightly out of focus, not only to take advantage of increased relief contrasts and color effects but also because it is a considerable nuisance to do

anything else. I soon found, however, that though the sharpness of focus had no appreciable effect on results for coarse-grained minerals, values reproducible within the supposed analytical error of the method could be obtained on minor constituents only if the point counter was closely adjusted and the field was brought to sharp focus whenever it was necessary to decide whether a small grain was actually cut by the cross-hair intersection or not. Failure to observe these conditions results not only in erratic values but, in my case at least, seems to introduce a small positive bias in the estimates.

Shortly after completion of the Barre study the Westerly *b* and *c* series were cut and analyzed; in this and all subsequent work involving fine grains due respect has been given the adjustment of the counter and the focus of the microscope. Assuming that differences between *a* and *b* slides are negligible, as table 3 indicates to be the case for all constituents save muscovite, I now have a total of 33 thin sections of Barre, Westerly, and Bradford, each of which was run both before and after I had realized the importance of adjustment and focus. In 26 of the 33 paired analyses the earlier muscovite value is higher than the later one.

I believe the present results—that is, all dating from after the Barre study—are not only more consistent but also more correct than the earlier ones, and am reasonably confident that the point counter is much better for work on fine-grained constituents than any line integrator except possibly the Wentworth-Hunt instrument.

However this may be, the Westerly *a* values for muscovite differ decidedly from the *b* values and may not be used in further comparisons. Incidentally, just as we may test $(a–b)$ against theoretical analytical error to determine whether the time factor is strong enough to influence the result, we may also test $(b–c)$ to gauge the influence of spacing. Since *b* and *c* were done after the Barre study, there is no question of a time effect; and, if the hand specimens are truly homogeneous or their internal variation is too small to detect, analytical error ought again to account for the variation between them. For Westerly muscovite s^2 computed from $(b–c)$ is 0.120 while σ^2 is 0.127; there is here a good indication that with proper precautions error variance is the same for fine-grained constituents as for coarse ones.

THE PETROGRAPHY AND ENVIRONMENT OF DEPOSITION OF THE WARNER, LITTLE CABIN, AND HARTSHORNE SANDSTONES IN NORTHEASTERN OKLAHOMA

PHILIP C. SCRUTON

ABSTRACT. The petrography and field occurrences of the Warner, Little Cabin, and Hartshorne sandstones of lower Des Moines age in the area between Warner and Pryor in northeastern Oklahoma were studied in detail in order to determine the environments of deposition. On the basis of sedimentary structures, lithologic characteristics, fossil evidence, and areal distribution three environments of sand deposition are indicated. These are the river and submarine channel and the near shore neritic zone.

The environments of deposition indicated by these sandstones and their occurrence in a related association of other alternating marine and terrestrial clastics, thin and intermittent coal beds, and limestones show that the Des Moines series in the Warner-Pryor district, at least from the Atoka through the McAlester formations represents a delta of moderate size. The increase in the sandstone to shale ratio in columns along sections approaching the Ozark region indicates that the delta was built outward from this low positive area.

Correlation of particular beds in this delta by means of heavy minerals was not possible since the suite does not vary appreciably from the lower Atoka sandstones to the Bluejacket sandstone of the lower Boggy formation. The heavy mineral suite consists of leucoxene, varieties of zircon and tourmaline, muscovite, rutile, staurolite, and chlorite and was developed by deep leaching of pre-existing sedimentary rocks on the flanks of the Ozark Dome in a mild humid climate.

INTRODUCTION

THE sandstones considered in this paper outcrop in a narrow strip trending from north to south in northeastern Oklahoma which extends through Mayes, Wagoner, and Muskogee counties (fig. 1). They belong in the lower portion of the Pennsylvanian system and are of lower Des Moines age. They, together with thick shales, other sandstone members, and minor thicknesses of limestone and coal compose the Atoka, Hartshorne, McAlester, Savanna, and lower part of the Boggy formations (table 1).

Geologic work in eastern Oklahoma began early in the State's history, largely because of the coal resources of the region. Drake (1897) and Taff (1899, 1902a, 1902b, 1905, 1906) are notable among the early workers. The early work resulted in the subdivision and naming of the lower Pennsylvanian beds around

TABLE 1

Classification of Pennsylvanian Rocks
in Muskogee-Pryor District

	South of Arkansas River (T.12N.)		North of Arkansas River (T.16N.)	
Des Moines Series	Boggy Formation		Boggy Formation	
	Savanna Formation		McAlester-Savanna Formation	Little Cabin ss. member
	McAlester Shale	Warner ss. member		
	Hartshorne sandstone		?	
	Atoka Formation	Blackjack School ss. member	Atoka Formation	Blackjack School ss. member
	Morrow Series		Morrow Series	

the towns of Atoka, Coalgate, Hartshorne, and McAlester. Thom, Wilson and Newell (1937), Dane and Hendricks (1936), and Renfro (1947) extended these early subdivisions northward and mapped the area considered in this paper.

Successful subdivision of thick sediments requires that breaks in deposition which can be identified around the margin of the basin of accumulation be carried into the regions of essentially continuous deposition. Once the marginal relationships have been established, they may possibly be traced into the areas of continuous deposition and thus a fuller understanding of the thicker rocks found therein may be achieved. Considerable effort has been devoted in attempts to determine the precise southern equivalent of the Little Cabin sandstone because of its presumed importance in the successful subdivision of Pennsylvanian sediments.

A detailed knowledge of the relatively thin lower Pennsylvanian section below the Bluejacket sandstone of the Boggy formation in this area is of importance as it lies between exposures of lower Pennsylvanian rocks of Kansas and the thick sediments of the Ouachita Geosyncline. Understanding of this section is necessary in order properly to relate rocks to the north with their more imposing correlatives to the south.

Various obstacles have long stood in the path of successful correlation of beds across the Arkansas River north of Muskogee. The broad, late mature valleys of the Arkansas and Verdigris rivers at their juncture and the thick blankets of Quaternary alluvium which flank these streams have rendered surface tracing impossible. Lack of understanding of the nature of the beds and their environments of deposition has further

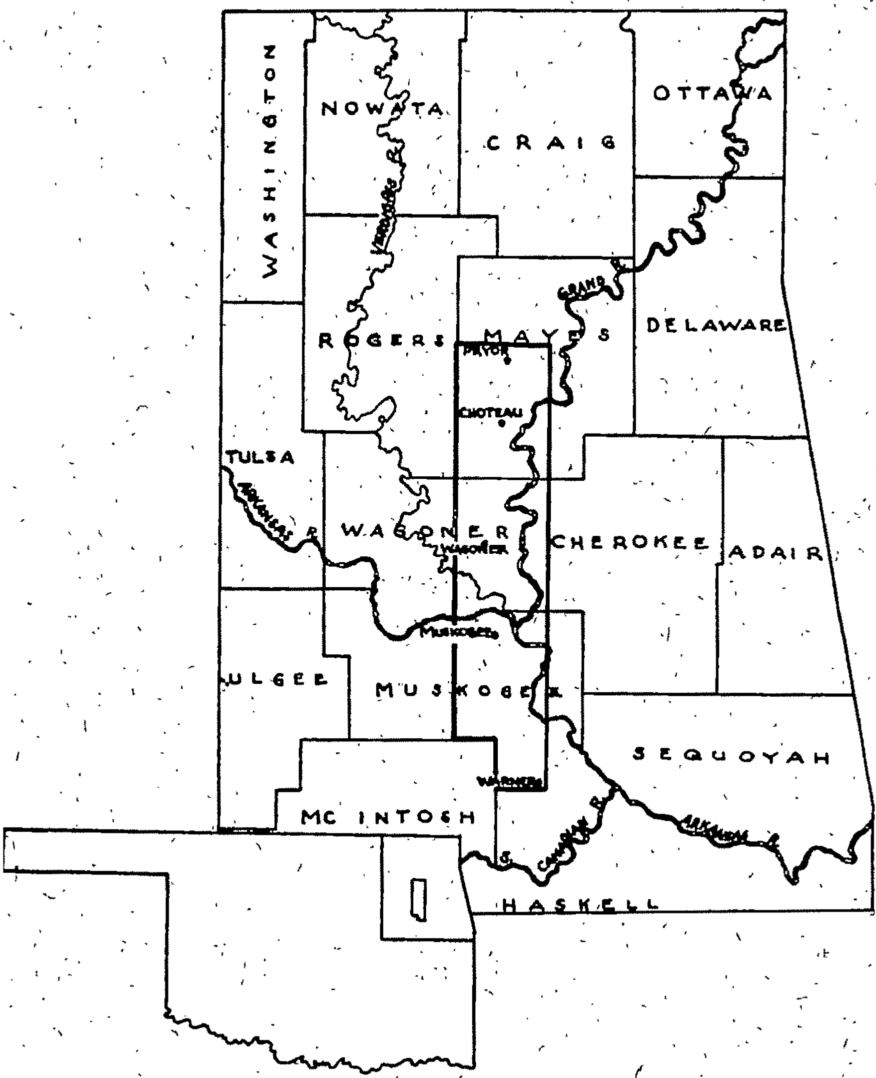

Fig. 1. Location of area.

increased the difficulty. Correlation of sandstones in this area by paleontologic means has proven to be impossible because animal forms change but little within the comparatively short time range represented by the section. Moreover, fossils are normally so poorly preserved as to be worthless for the extremely precise work which is necessary.

Correlation by petrographic methods has been attempted in other areas where similar difficulties have been met, and in many cases has been found successful. In this investigation the petrography and stratigraphic relations of the Warner, Little Cabin, and Hartshorne sandstones have been examined to determine whether correlation of these beds by this means is feasible. From these petrographic and stratigraphic considerations, knowledge of the nature of the organic remains, and a review of the physical framework of the region during the time of deposition, it is believed that some knowledge of the environment of deposition, the source beds for the sediments, and the paleoclimate and the paleogeography may be acquired. This knowledge may give a clearer picture of lower Pennsylvanian history in northeastern Oklahoma and the adjoining region of Kansas.

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PROCEDURE

Series of samples were collected from outcrops of the Warner and Hartshorne sandstones south of the Arkansas River and from the Little Cabin sandstone north of this river. A split of fifty grams was prepared from each sample and gently mashed in a mortar. The partially disaggregated material was then boiled in 6N hydrochloric acid to complete separation of the grains and to remove iron oxide which serves as a cement in the sandstone. After this oxide was removed, the solution and residue were diluted to 600 milliliters and decanted after settling for 30 seconds. This procedure removed particles below 1/16 mm. in diameter. After drying, the residue was weighed to determine loss in solution and decantation and passed through a battery of 20, 40, 60, 80, 100, and 200 mesh

screens. The portion retained on each screen was weighed to determine percentage.

Sand which passed the 100 mesh screen but was retained on the 200 mesh was treated with bromoform to separate the heavy minerals. Permanent mounts of these were made, and the suites were analyzed and grain counts made by use of the petrographic microscope.

DESCRIPTION OF MINERALS

The mineralogy of the Hartshorne, Warner, and Little Cabin sandstones was found to be essentially uniform. For this reason the minerals of the three sandstones are discussed under a single heading, with any peculiarities present being noted in the treatment of the particular mineral where the irregularity occurs.

Quartz. In all of the samples analyzed, quartz is in the dominant mineral. The grains vary in shape from highly rounded to angular. Pitted and striated grains are common, and well developed frosting is almost universally present on the larger grains. It is also present on many of the smaller grains. Authigenic quartz in optical continuity is present on many grains to the point of developing perfect prismatic crystals doubly terminated by positive and negative rhombohedrons, and is usually set off by a well marked encirclement of the core by ferruginous or argillaceous material. In some cases this grain covering of foreign material is so complete that the inner core could exert no control on molecular arrangement of the silica being deposited and optical discontinuity resulted. Several samples contained quartz which exhibited a peculiar gray color in the leached aggregate. This proved to be due to an original-grain shroud of white argillaceous material completely surrounded and protected from leaching by a film of authigenic quartz. If the covering of secondary material is well developed, details of the surface texture on the original grain cannot be distinguished. The presence of secondary quartz is most prominent in samples taken from south of the Arkansas River but is also present in many of the samples from the northern part of the region.

Chert. Chert is second in abundance to quartz, and chert grains are more prominent in the samples collected north of the Arkansas River. Particles normally are quite angular

and show little or no evidence of rounding. In a few cases chert served as a cement for grains of quartz and formed a hard resistant rock extremely difficult to disaggregate.

Feldspar. Grains of albite feldspar were observed in only one sample. All grains were very angular and generally unaltered except for two which showed clouding due to decomposition products.

Leucoxene. Leucoxene is commonly the dominant heavy mineral. It occurs in a variety of forms and has color ranging from white through grayish white to faintly pink or orange. Shape ranges from well rounded to angular; the well rounded grains are probably of detrital origin. Grains of ilmenite were found in all stages of alteration to leucoxene and grains of staurolite were seen partially covered with a white, leucoxene-like film. Leucoxene has often been the center of deposition for a clear unclouded layer of secondary quartz. The quantity of leucoxene averages roughly 40 per cent greater in samples taken from north of the Arkansas River.

Muscovite. This mineral is often next in quantitative importance to leucoxene and in some cases exceeds it in quantity. It is present in all samples in highly variable percentages. Occurrence is in the form of clear, colorless, subrounded to subangular books with slightly abraded edges. Inclusions are very common and are either clear, needle-like, and transparent or black, spherical, and opaque. Undulatory extinction is very common. The occurrence of muscovite seems to be related more to average grain size of the sample and nature of the heavy mineral suite than to the geographic distribution of the samples. Muscovite is present in large percentages if the median grain size is very low and the heavy mineral suite is small. Conversely, if average grain size is high and a well developed heavy mineral suite is present, the percentage of muscovite is low. These facts clearly indicate that muscovite, although ubiquitous in the transporting agent, was only deposited when the competency of this medium was very low as would be expected from a consideration of the shape and specific gravity of the mineral.

Staurolite. Normally next in importance in the heavy mineral suite is staurolite. This mineral is gold to brownish gold in color and subangular to angular in shape. Well-rounded grains

of staurolite were not observed. The varieties which are darker in color transmit light with difficulty. Grains showing twinning and those with no trace of twinning lamellae are about equal in quantity. These latter fragments exhibit well developed conchoidal fracture and normally contain inclusions. These are either small, prismatic, doubly terminated, clear, colorless zircons or round transparent forms which seem to be oriented along crystallographic lines of control. There seems to be no geographical pattern to the distribution of staurolite.

Zircon. Zircon in variable quantity was noted in every sample. Shape varies from extremely well rounded spherical grains, well rounded prismatic crystals, irregular subangular fragments, to perfectly euhedral doubly terminated crystals. The last are not common. Color ranges from clear and colorless to faintly bluish to strongly pink or purple. Only the perfectly clear and colorless grains were seen as euhedra; all colored grains show some abrasion. In two cases small pyramidal projections were noted on otherwise highly spherical grains. These appear to have grown out from the grain in a direction parallel to the c-axis and were taken to be developments of authigenic zircon.

A definite geographical relationship exists in the ratio of colorless to pink zircons. The highest percentage of pink zircons and their best physical development were found in the samples taken from the Little Cabin sandstone in the northern part of the area. They were found only sporadically in the Warner sandstone to the south and were not observed in the Hartshorne sandstone. In connection with this study some of the lower sands of the Atoka formation south of the Arkansas River were analyzed for heavy mineral content. Exactly the same suite was found in these lower sands as occurs in the Warner sandstone. Thus, the absence of pink zircon in the Hartshorne and its later appearance in the Warner does not indicate a new source of sediments or the entrance of a new element into the suite.

Tourmaline. Six varieties of tourmaline were found to be present.

1. *Brown.* The brown variety of tourmaline varies from a rather dark brown to pale honey-yellow, depending on the optical orientation, and is subround to subangular in shape.

Inclusions, both spherical and opaque and spherical and clear, are commonly present. Their arrangement is normally parallel to the long axis of the crystal.

2. *Greenish-brown.* With the exception of color, this variety is like the brown tourmaline described above.
3. *Brownish-green.* This variety differs from the above in color only.
4. *Green.* Grains of this variety are subround to subangular in shape and clear green to pale amber-tinted green in color, depending on the orientation of the fragment.
5. *Purple.* The color varies from deep purple to only faintly so. In shape the grains are subangular to subround. Clear spherical inclusions aligned with the c-axis are common.
6. *Indigo blue* (Indicolite). Fragments of this variety are consistently a clear light blue. Grains are normally well rounded with inclusions of colorless material present. The surface of some of the grains is quite rough. There seems to be some geographic control of the frequency of occurrence. Indicolite is moderately common in suites from samples of the Little Cabin sandstone but is less common from samples of the Warner sandstone to the south and was not found in the Hartshorne. It was found in the lower Atoka beds so that its reappearance in the Warner seems to signify only a return to the site of deposition of a more competent transporting agent.

Rutile. The rutile grains are normally very well rounded and dark reddish-brown in color. Because of its intense color the mineral is nearly opaque, but under reflected light or in the conoscope the true color of the individual grains becomes apparent. An increase in quantity of rutile south of the Arkansas River was noted.

Ilmenite. Ilmenite and magnetite were not differentiated. The minerals occur as completely opaque rounded grains showing a metallic luster in reflected light. All degrees of alteration to leucoxene are present.

Spinel (variety picotite). One fragment of a coffee brown, angular, isotropic mineral with conchoidal fracture, high index of refraction, and several clear spherical inclusions was observed. This grain was provisionally identified as spinel.

Chlorite. No chlorite was found in the heavy mineral separations made from the sand of grade size used for separation, but a few large books of dull grayish-green chlorite were observed under the binocular microscope.

All attempts to correlate the Little Cabin sandstone with the Warner or Hartshorne sandstones on the basis of heavy minerals met with failure. In all of these sands the heavy mineral suite is either uniform or the lack of uniformity has no significance in correlation. No new species or variety of mineral has been found to enter and none of those present leaves the assemblage through the vertical interval studied. Any attempt to correlate on the basis of mineral percentages was equally futile. The percentages of the various species present have been found so variable in the different beds that in many cases Hartshorne percentages correspond as closely to those derived from a Warner sample as do percentages derived from other Warner samples. Incomplete study of the lower

TABLE 2

Results of Mechanical Analysis. Percentage of 50 Gram Sample by Weight in Each Grade Size

Sample Numbers		Grade Size: 20	20—40	40—60	60—80	80—100	100—200	Pan	Loss in Solution & Decantation
Hartshorne	1	—	0.6	4.7	4.1	6.7	49.5	20.8	13.4
	2	—	1.4	12.2	11.2	28	30.8	5.6	11.6
	3	—	1.4	16.6	9	6.2	14.8	17.8	34.4
	4	—	—	7	5	9	27	35	17
	5	—	—	5	6	7	11	30	41
Warner	8a	1.7	11.4	24.9	17.9	14.3	12.5	4.9	14.3
	12	—	2.6	38.6	47.3	2	3.2	1	7
	13	—	0.5	11.6	13.8	42.8	21.8	3.8	5.9
	14	—	3.1	47.7	32.5	2.4	5.3	1.6	7.2
	15	—	13	46	25	6	4	1	3
	16	—	—	8	5	6	28	20	33
Little Cabin	9a	—	0.7	6.7	7.1	17.7	32.3	4.1	31.1
	10	—	1.3	8.8	15	37.7	25.0	3.3	8.6
	11	—	1.9	17.6	24.3	20.7	13.5	7.4	14.3
	17	—	8	14	9	8	24	19	17
	18	—	—	10	13	31	22	4	19
	19	4	29	24	12	7	5	1	16
	21	—	1	11	5	6	13	35	29
	22	—	1	12	32	29	7	2	16

sands of the Atoka and the Bluejacket member of the Boggy formation indicates that there is no change in the heavy mineral assemblage in the entire section. If later study bears out this indication, dependable petrographic zoning is impossible in all of the lower Pennsylvanian section in this area.

GENERAL FIELD OCCURRENCES AND RELATIONS

Study of the various sandstones of the Little Cabin-Warner-Hartshorne sequence on the outcrop and in the laboratory shows that there are two general lithologic types of sand with all possible gradations and variations between them. These are designated the Hartshorne facies and the Warner facies.

The Hartshorne facies is characteristic of the Hartshorne sandstone and is also very common in the Little Cabin sandstone. This type of sandstone is characterized by poor sorting, fine grain size, poor to fine lamination, and large quantities of silt, clay, and limonite. The limiting bedding planes

TABLE 8

Heavy Mineral Percentages Based on Counts of 300 Grains

ample	Numbers	Muscovite	Tourmaline Br.	Tourmaline Gr. Br.	Tourmaline Br. Gr.	Tourmaline Gr.	Tourmaline Pur.	Tourmaline Ind. Bl.	Zircon	Rutile	Leucoxene	Ilmenite	Staurolite
artshorne	1	1	*	*	—	*	—	—	26	18	40	4	12
	2	1	*	—	4	1	2	—	5	7	64	5	10
	3	41	—	2	8	—	—	—	7	5	29	3	11
	4	8	1	*	*	1	—	—	14	6	67	—	2
	5	85	1	—	*	*	—	—	*	2	10	—	—
arner	8a	*	6	4	—	—	3	*	8	8	46	13	12
	12	16	—	4	2	*	*	—	5	4	38	5	25
	13	*	1	*	—	—	8	*	17	5	58	9	6
	14	6	—	*	—	*	*	—	30	16	31	6	10
	15	3	2	2	2	2	2	—	2	4	71	10	—
	16	52	1	—	*	1	*	—	7	3	35	1	—
ittle Cabin	9a	1	2	4	1	*	3	1	8	5	70	2	8
	10	4	8	—	—	*	4	2	10	7	61	2	6
	11	24	—	6	—	4	*	1	22	2	35	2	2
	17	28	*	—	*	—	—	—	5	3	62	1	—
	18	3	1	1	1	1	1	1	12	2	65	1	11
	19	—	1	1	—	2	1	2	23	4	32	6	28
	21	77	*	—	*	—	—	—	3	*	77	—	1
	22	5	3	2	1	1	1	*	7	3	62	4	11

Trace, less than 1 per cent. Key: Br. Brown; Gr. Green; Gr. Br. Green-Brown; Pur. Purple; Br. Gr. Brown-Green; Ind. Bl. Indigo Blue

of a major unit may be well developed or the sandstones may grade progressively into shale. This gradation is most often basal and into underlying beds, but gradation into overlying units has also been observed. Exposures of the thinly bedded material are usually capped by a more massive bed of variable thickness which is generally lensing in nature, and from which the fine grained material is separated by a well marked break characterized by cut-and-fill structure. The heavy mineral yield of the Hartshorne facies consists primarily of muscovite, leucoxene, and minor amounts of other materials. Land plant remains are very common, and fucoid markings on the bedding planes are frequently encountered. Linguloid type ripple marks and mud cracks have been found. In some cases the Hartshorne facies can be seen at generally the same topographic level as beds of the other facies.

The Warner facies is characteristic of the Warner sandstone and less so of the Little Cabin sandstone. The Warner facies, in ideal development, is characterized by rather good sorting, medium grain size, relatively unimportant quantities of silt and clay, localization of iron oxide (limonite) into beds and more rarely concretions, and excellent development of the heavy mineral fraction with little muscovite and, in some cases, relatively little leucoxene. A lens defined by well marked stratification often has excellent development of the graded type of bedding, with a particular lamination showing progressive change from medium grain size through fine grained sand to an iron rich layer of fine grain size. This succession is often overlain by a repetition of a similar sequence. The capping iron rich portion of the lamination is often not developed and when this is the case the individual layer varies from medium to finer grained sand. Warner facies development in the Little Cabin sandstone often shows small lenses and pockets of granule conglomerate with subrounded to rounded quartz granules set in a matrix of finer grained material. Fossil content of the Warner facies is normally low. Plant remains have been found although these are not well preserved. At some localities brachiopod, bryozoa, echinoderm, and mollusk remains have been collected. There seems to be little uniformity of type of life represented and marine and terrestrial fossils occur in the same bed and sometimes in the same locality. Rough cut-and-fill structure, cross-lamination, and rapid lensing of

the units is common. The top of a bed often shows wave-type ripple mark. At the type locality of the Warner just north of the town of Warner a peculiar hassock-like structure occurs in the formation. The sand at this locality is well developed Warner facies showing both complete and incomplete graded bedding. The individual beds have been deformed and contorted until they resemble Appalachian folding in miniature. This peculiar situation can best be explained as pre-lithification sliding on a gently inclined slope. The Warner facies is separated from units above and below by sharp breaks and nowhere has been seen to grade into other types of deposits, although, as has been noted, deposits of the Hartshorne facies can be seen lying at similar topographic position with no structural offset between.

The typical Warner facies varies greatly in overall thickness. In the region around Warner it attains a maximum thickness of some 25 feet. To the north in the Little Cabin sandstone it varies from only a few inches to a maximum of ten feet.

Over most of the area under study the Warner facies is a very resistant sandstone which controls the topography. Hills capped by this sandstone normally show a long and a short horizontal axis. The long axes in the area around Choteau are generally aligned from N.80°E. to N.50°E. Hills of this nature around Wagoner show major axial alignment which is generally N.30°E. to N.50°E. South of the Arkansas River the alignment of the topographic highs seems to be present but is different in direction, being either roughly north-south or east-west. The hills from Choteau to south of Wagoner are smaller than those below the Arkansas River and display definite inequalities in the horizontal axes. The width of these hills controlled by sand bodies is of the order of magnitude of 100 yards with the lengths ranging up to one-half mile. The corresponding highs in the southern part of the area are roughly two to five miles long and of less width. Since the sand units which cap the topographic highs can be seen to thin laterally, it may be inferred that they originally existed as lensing, more or less discontinuous bodies in a mass of less resistant shale. It is felt that these sand bodies indicate the principal courses of the transporting agent and the main sites of clastic deposition at a particular time.

The color of both Hartshorne and Warner facies on the surface outcrop is highly variable. The Hartshorne type varies from a dark brown to dark green, through olive brown to a pale buff. The Warner type of sand does not show the dark green, but is normally brown to dark or light buff and may be deeply red. With the possible exception of the dark red and dark brown seen in the Warner type, it is believed that the colors are primarily due to surface weathering. The quantity of organic material buried with the sediments undoubtedly brought about reduction of the iron which is the chief coloring agent in the beds. This idea is borne out by microscopic examination of subsurface samples from wells which penetrate these formations. The unweathered material thus obtained, often well cemented with calcium carbonate, shows a uniform light to medium gray color for the sandstones.

The above are the two major types of sandstone present in the area, but there are all possible gradations within and around these types. The occurrence of one type is not restricted to any one horizon. One type may be found lying immediately adjacent to the other, either above, below, or laterally within a single unit. The Hartshorne facies may grade into shale or impure limestone, but the Warner facies is always separated by clean breaks from underlying and overlying beds. Consideration of lateral distribution and variation leads to another conclusion. These sandstone beds, instead of being the result of a single environment of deposition, are actually the products of at least three environments, all closely related in space. The Little Cabin, with its subparallel ridges of coarse-grained, cross-laminated, cut-and-fill, fossiliferous, modified Warner type sandstone is the product of the river channel and the submarine channel with their near channel associates. The Hartshorne, although its outcrops are less well exposed, shows almost a full range of lithic parallelism with the Little Cabin and is undoubtedly of similar origin. The Warner sandstone departs from the other two in type of outcrop pattern and in overall lithology and is best explained as the product of deposition in the near shore neritic zone. The more regular bedding, the better sorting, the evidence for prelithification sliding, and the greater areal extent and uniformity all indicate this.

RELATIONS BETWEEN THE HARTSHORNE, WARNER, AND LITTLE CABIN SANDSTONES AND ASSOCIATED BEDS

In order to understand the environment of deposition of a single bed or of a single group of beds within a continuous period of sedimentation, it is necessary to examine, not only the bed or beds in question, but also, the gross field relations between all of the members of the depositional unit. In addition, the formation, transportation, and deposition of sediments within a province is, in a large measure, a function of the physical environment of the province. The types of sediments which are formed, their mode of transportation to the sites of ultimate deposition, and the nature of the deposit thus formed are all possible because of response by one part of the physical environment to the other parts. The rocks themselves react to the agents of climate and geography which make up or control the remainder of that physical environment. Thus, the starting point for reconstruction of an ancient deposit is a review of the paleogeology and paleogeography of the province.

Dott (1928) shows that in lower Pennsylvanian time a seaway lay several miles to the south of Muskogee against the flanks of the positive Ozark Dome and thence extended almost due east into Arkansas. Maps of later stages show the strand line slowly advancing to the north and west. Thus, the physical framework of the area was suitable for the formation, transportation and deposition of sediments. With the thick limestones, shales, cherts, and thinner sandstones of the pre-Pennsylvanian Ozark Dome bared for denudation, an ample source of detritus existed, and with the seaway lapping against its feet, a ready site of deposition was at hand.

An investigation of the lower Pennsylvanian beds shows them to be of complex and variable character. With the exception of products of vulcanism and evaporation and perhaps rare chemical deposits, it is probable that every known type of sediment can be found in some degree of development. Organic sediments as coal and petroleum, bio- and physico-chemical carbonates, the entire range of clastics, siliceous, and ferruginous deposits, all are known within a matter of a few hundred feet of beds deposited within a single geologic epoch in a single locality. A section, 87′ 5″ thick, measured

along the south line of sections 34 and 35, T.20N., R.18E. effectively illustrates the rapid vertical variations of the beds in the entire area.

Zone	Description	Thickness
14.	Silty, unevenly bedded, buff to brown sandstone. Small nodules of clay common. Cut-and-fill structure, mud cracks, and linguloid ripple marks prevalent	3′ 5″
13.	Thin bedded, olive to brownish buff, silty shale with thin lenses of sand	4″
12.	Lensing unit of buff, clay-ball conglomerate. The matrix is an argillaceous, fine grained sandstone with compact balls of gray clay similar to (9)	0–5″
11.	Layer of concentric ironstone concretions	2″
10.	Black unfossiliferous paper shales	10″
9.	Gray to buff, poorly bedded, leached, plastic clay. Iron concretions common	8″
8.	Above grades into gray to black to brown shales	47′
7.	Ferruginous, brachiopodal limestone	4″
6.	Buff to black shale	11″
5.	Lignitic coal	3″
4.	Gray, iron stained plastic underclay	6″
3.	Gray to buff silty shale	20′
2.	Massive, lensing, buff, medium grained sandstone	2′
1.	Fine grained, thinly bedded, olive to buff sandstone	10′
	Total	87′ 5″

This section overlies the Morrow limestone and is in no way unique. Newell (Wilson and Newell, 1937, p. 155ff.) gives a number of carefully measured sections from south of the Arkansas River which display variations in lithology equally as great within a similar interval.

The extreme variation of the sediments is not restricted to the vertical plane but is also well developed laterally. It has long been recognized that the lower Pennsylvanian sandstones of eastern Oklahoma have little or no persistence, either along the strike or the dip. They normally show crude cross-lamination and cut-and-fill, and tend to thin and thicken rapidly, and to pinch out completely in all directions. Examples of this lensing nature of the sandstones have been cited above. The shales, coals, and thin limestones seem to be little more reliable as horizon markers. In the region south of the Arkansas River, the shales constitute the major portion of the section and exhibit little resistance to erosion, so that poor outcrops are the rule. The presence of stray sands, thin coals, and limestones within these shales indicates that what is true for

the sands is equally true for the shales. In some cases the coals are more reliable as horizon markers. However they do not escape the general tendency to be highly discontinuous. The coals of the Hartshorne, McAlester, Savanna, and lower Boggy formations are all locally developed and not continuous. The thin limestones of the McAlester and Savanna formations are also subject to lateral variation.

The general thinning of the lower Pennsylvanian section from south to north in northeastern Oklahoma has been recognized. However, a particularly significant fact in the general relationship has not been interpreted. The thinning which is registered in the section is accomplished almost entirely within the shale units. The nature of the change in the rocks from south to north is best illustrated by several generalized sections. In T.12N., of the 700 odd feet of beds from the top of the Morrow to the top of the Warner, some 100 feet is sandstone while the remainder is largely shale. The sandstone to shale ratio here is 1:7. In T.14N. the same section is 600 feet thick with a general thickening of the total sand section resulting in an increase in the sandstone to shale ratio. In T.16N. the situation has changed radically. The total section from the top to the Warner to the base of the Atoka is about 400 feet thick. Of this thickness, the sandstones make up 170 feet. Thus the ratio of sand to shale is roughly 1:1 and there is relatively seven times as much sand in the section as in T.12N. This increase in the clastic nature of the section toward the north indicates that the source of these sediments must have been in this direction. This conclusion is strengthened by the complete absence of garnet in the samples studied. This mineral is characteristic of Silurian and later rocks to the south and would be expected in these sediments had they been transported from this direction.

In reconstructing the environment of deposition of a series of beds, consideration must be given to the organic remains found in them. In connection with the field work for this paper, fossils were examined from the base of the Atoka to the top of the Warner or Little Cabin sandstones over the entire area. In every bed of the Atoka which was examined it was possible to find a more or less abundant and balanced assemblage of undoubted marine fossils. At the general level of the Hartshorne, however, a change is suggested. Coal lies both above and

below the Hartshorne sandstone. The sand itself yields abundant plant remains with specimens of *Lepidodendron* particularly prominent. In the Muskogee area no fossils were found in the Warner but almost directly overlying this unit at several localities are lenses of coal. Overlying these coal lenses are undoubted marine beds such as the Spaniard limestone. In the northern part of the area similar conditions exist. In the Little Cabin sandstone both marine and terrestrial plant fossils have been collected, sometimes one type to the exclusion of the other and sometimes both types together. The detailed section given above shows a variation from continental to marine beds, through other continental and marine units up to more continental strata in the ascending sequence.

From this review of the condition as expressed by fossil content of the beds a certain pattern becomes apparent. The beds of the Atoka are dominantly marine in origin, but the sequence of events in post-Atoka time is a highly complex blending of happenings with marine or terrestrial environments prevailing at one point at successive times. Study of the fossil content of the Little Cabin sandstone and associated beds shows that this same vertical variation of environments is also present laterally.

Consideration of sedimentary structures, lithologies, petrography, colors, distribution, and fossil content has indicated three environments of sand deposition. To these must be added the environments in which mud, swamp, and reasonably clear water deposits were made, now present in the form of the shales, coals, and thin limestones.

Creation of order from this complexity appears difficult. However, when all of the evidence is considered, it seems very probable that the site of deposition was a region where a river, or group or rivers, flowing generally southwest off of the positive Ozark Dome entered the sea. At some place within the area every characteristic feature of the deltaic environment can be found.

INTERPRETATION OF GEOLOGIC HISTORY

The existence of a delta of moderate size on the southwestern flank of the Ozark highland has thus been virtually demonstrated. The shallow lower Atoka sea advanced from the southwest to the flank of the Ozark Dome north of Muskogee and east of Wagoner. This general limit of advance was main-

tained during the period of deposition of the lower Atoka members. Slow sinking of an epeirogenic nature is indicated by the gradual transgression of upper Atoka beds to the north and east over the older members of this formation. Deposition following the Atoka, in general, seemed to catch up with subsidence and began locally to force the seas back to the south and west. Sedimentation may have been aided locally by gentle crustal warping in causing these restricted retreats of the sea. However, continuation of the downwarping, in general, spread the sea farther to the north along the western margin of the Ozark area. Deposition at times lagged behind sinking and reinvasions by the sea produced interfingering of marine and terrestrial sediments. The general position of the coast line at this period is delineated with some degree of precision by the eastern limit of the Little Cabin sandstone which was laid down near the shore, at some places on the subaqueous plain and at other places on the subaerial plain. Continued downwarping after Little Cabin time appears to have resulted in a more extensive invasion of the Ozark Dome, further northward extension of the coast line, and in the deposition of another series of marine beds.

The Ozark region was never high during this period. Undoubtedly it was a very low-lying land with subdued topography. If the crystalline core of the Ozarks was exposed to denudation at this time the drainage from these rocks was in another direction. No evidence of undoubted first cycle minerals was found in any sample. Instead, it seems that sedimentary rocks furnished the material for deposition since only resistant minerals were found.

The streams bearing sediments meandered from the Ozark region to the sea with very low gradient. Carbonates, colloidal silica, iron salts, fine clay, silt, and some sand made up the bulk of the load. This type of burden was conditioned by the gentle slope of the land and the low stream gradient, the equitable climate which permitted abundant plant growth and deep leaching, and the source rocks themselves. The predominantly limestone and chert sequence of the Ozarks could not be expected to furnish great quantities of pure quartz sand under any conditions of slope or weathering. The older quartz sandstones would, of course, yield some material of this nature, but the clastic load would consist to a large extent of the chert and insoluble clay residues found in the limestone. Review of

the stratigraphic section and the mineralogy of the sandstones shows that these products are exactly what are represented. The abundant secondary silica, iron oxide, and calcium carbonate cement in the sands and shales are the result of precipitation from solution and colloidal suspension of these materials by salt or brackish waters and their entombment at the site of deposition.

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GROWTH STAGES IN FOSSIL OSTRACODES*

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ABSTRACT. Principles for the rate of growth in Arthropoda as applied to ostracodes, the number of growth stages that occur, and growth factors (the percentage of increase in size between growth stages) are discussed. Hans Przibram's growth factor of 1.26 for all Arthropoda is proved, according to available data, not to apply to ostracodes. Limitations inherent in the study of growth stages of fossil ostracodes are pointed out.

THE fact has been known for a long time that ostracodes, in common with other members of the phylum Arthropoda, undergo periodic molting in order to change in size, and have several instars during the course of their development. The terms "growth stage (instar)" and "molt stage" have been used synonymously. I shall use these terms as defined in Webster's New International Dictionary, 2d edition, unabridged:

"Instar: An insect or other arthropod in any of the several forms assumed between the successive ecdyses, or molts; hence, the form assumed during one such stage, or the stage itself."

"Molt: *v.* To shed or cast off the hair, feathers, outer layer of skin, horns, or the like, the castoff parts being replaced by new growth.

n. The act or process of molting; also, the castoff covering."

As early as 1849, Jones (1849 pp. 18-19) recognized and designated "young", "immature", and "adult" stages of growth in *Cythereis quadrilatera* Roemer, and *C. ciliata* Reuss. Subsequent workers were not always able to associate forms that differed in size, shape, ornamentation, and hinge structure as stages of growth in the same species, and as a result some genera and species were erected on the basis of immature individuals.

During the past decade the study of growth series has resulted in the revision, suppression, and redefinition of some of these genera and species. Le Roy (1945) studied the development of *Cythereis simiensis* (Le Roy) and *C. holmani* Le Roy, and Cooper applied the principle of growth series to

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species of *Hollinella* (1946, pp. 87-97) and traced the development of *Ectodemites plummeri* Cooper (1945).

A principle for the rate of growth of Arthropoda was formulated for the first time in 1886 by Brooks (1886, p. 5). In his work on *Coronis* larvae he noted that by multiplying the length of the first growth stage by five-fourths, and the product by five-fourths again, and so on, a series of numbers that approximated the measured lengths of successive growth stages was obtained. In 1909, Fowler (1909, p. 224) published his results on living ostracodes that were captured in the Bay of Biscay and stated: "During early growth, each stage increases at each molt by a fixed percentage of its length, which is approximately constant for the species and sex." He named this principle "Brooks' Law." Fowler's growth factors for species of *Halocypridae* range from 1.26 to 1.78. Przibram (1931, p. 26) arrived at the growth factor of 1.26 for all Arthropoda, because 1.26 is the cube root of 2.0. He assumed that Arthropoda molt when the mass is doubled. "Any body which without change of form increases its volume to the double, will increase its length only by the cube root of two. Not only the length, but every line homologous in the original, will have to follow this same rule."

The question has been raised as to the number of growth stages that occur in ostracodes. The answer obviously lies with the zoologist, and, so far as I can determine, satisfactory data on the subject are not available. Workers on living ostracodes recognize up to nine stages (eight molts) to maturity, and apparently have not followed the development after sexual maturity is reached.

Available data seem to indicate nine stages to maturity in fresh-water ostracodes and only eight in marine forms (table 1). This fact should be checked by zoologists. In 1894 Müller (pp. 187-188) denied molting after maturity in most of the ostracodes ("Fur die meisten Ostracoden"), because he did not find discarded valves in aquaria in which he kept adults for several months. He suggested that in most *Cytheridae* and in some *Cypridae* the extensive fusion of the inner and outer lamellae that takes place in the adult stage makes additional molting highly improbable. In 1927, Müller (1927, p. 422) categorically denied molting in all ostracodes after maturity (Geschlechtsreife-puberty) is reached, without citing evidence to support the statement.

In 1948 Kesling (pp. 1332-1333) studied cultures of living *Cypridopsis vidua* and arrived at the conclusion that in this species the adult does not molt.

With regard to Müller's first statement and to Kesling's conclusion, the following facts should be borne in mind: They observed specimens in an aquarium and consequently out of their natural environment. The molting behavior may not necessarily be the same in captivity as in the natural environment. Müller's argument that extensive fusion of the duplicature prohibits further molting should be reexamined because during molting the entire exoskeleton is discarded (Sharpe, 1918, p. 798); a fused duplicature should not affect that process.

Post-maturity development is important to the paleontologist, because certain deductions depend on whether or not there were molts after maturity. Blake (1930) used Müller's 1927 statement in order to discredit Kellett's remark that "The frequent moulting of ostracodes would allow for the change in the female from the wide to the narrow frill" (1929, p. 198). Cooper (1946, p. 89) based his revision of the species in *Hollinella* partly on Müller's premise.

Dr. W. L. Schmitt, Head curator, Department of Zoology, U. S. National Museum, informed me[1] that other groups of Arthropoda molt in order to change in size after maturity is reached. Calvert (1929, pp. 246-249) cites considerable evidence that in Arthropoda molts are not absolute indicators of biologic age, that there can be molting without growth, growth without molting, and that there are reasons to believe that molting is an excretory process.

Although the answer to the question as to the number of molt stages in ostracodes awaits further investigation by zoologists, I would guess that in fossil ostracodes there probably were molt stages after maturity was reached.

Does the growth factor of 1.26, as postulated by Przibram, apply to ostracodes? Some data are available on the development of living ostracodes. The growth stages of a few species have been observed in the laboratory and in some cases checked against field collections. Data for the size of valves in the various growth stages have been recorded (table 1).

[1] Oral communication.

A graph showing the calculated values for nine growth stages having a growth factor of 1.26 can be constructed. With one as a unit, I multiplied it by 1.26 and obtained the scale value on the graph for the second growth stage. This value times 1.26 gave the value for the third stage, and so on for the scale values on the graph for the nine stages (fig. 1). The published data on the length of valves in successive growth stages were converted to the scale of this graph as follows: Growth factors between any two stages were obtained by

TABLE 1

Measured lengths (L) of growth stages of living Ostracodes and calculated growth factors (GF)

	Stage 1 L	GF	2 L	GF	3 L	GF	4 L	GF
Bairdia serrata[1]	0.2mm	1.30	0.26mm	1.23	0.32mm	1.22	0.39mm	1.33
Cythere lutea[2]	0.156	1.21	0.188	1.19	0.224	1.14	0.255	1.16
Cytherura nigrescens[2]	0.103	1.11	0.114	1.14	0.130	1.22	0.158	1.27
Hirshmannia viridis[2]	0.130	1.11	0.144	1.18	0.170	1.15	0.195	1.22
Loxoconcha impressa[2]	0.136	1.06	0.144	1.25	0.180	1.20	0.216	1.20
Loxoconcha impressa[1]	0.1	1.40	0.14	1.43	0.2	1.20	0.24	1.17
Macrocypris succinae[1]	0.29	1.28	0.37	1.19	0.44	1.21	0.53	1.19
Cyprinotus incongruens[3]	0.19	1.32	0.25	1.15	0.288	1.28	0.368	1.35
Cypris fasciata[4]	....	....	0.27	1.26	0.34	1.29	0.44	1.36
Cypris ovum[4]	0.132	1.25	0.165	1.15	0.19	1.21	0.23	1.17

	Stage 5 L	GF	6 L	GF	7 L	GF	8 L	GF	9 L
Bairdia serrata[1]	0.52mm	1.27	0.66mm						
Cythere lutea[2]	0.296	1.27	0.375	1.25	0.470mm	1.23	0.578mm		
Cytherura nigrescens[2]	0.200	1.18	0.236	1.22	0.287	1.26	0.361		
Hirshmannia viridis[2]	0.238	1.24	0.295	1.19	0.350	1.24	0.434		
Loxoconcha impressa[2]	0.260	1.22	0.316	1.19	0.375	1.24	0.463		
Loxoconcha impressa[1]	0.28	1.32	0.37	1.16	0.43	....	....		
Macrocypris succinae[1]	0.63	1.27	0.8	1.15	0.92	....	....		
Cyprinotus incongruens[3]	0.496	1.23	0.608	1.32	0.8	1.26	1.008	1.59	1.6mm
Cypris fasciata[4]	0.6	1.33	0.8	1.31	1.05	1.38	1.45	1.38	2.00
Cypris ovum[4]	0.27	1.30	0.35	1.29	0.45	1.20	0.54	1.11	0.6

[1] Müller, G. W., Uber Lebensweise und Entwicklungsgeschichte der Ostracoden: Sitzungsberichte Königlich Preussischen Akademie der Wissenschaften zu Berlin, vol. 13, pp. 368-375, 1893.

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dividing the length of the larger stage by the length of the preceding stage. The value of one on the scale of the graph was assigned to the first growth stage: this was multiplied by the factor between the first and second stages. The product is the scale value on the graph for the second growth stage. The scale value of the second growth stage times the growth factor between the second and third growth stages, and so on, equal the scale values on the graph for successive growth stages. The points thus calculated for several species of living ostracodes are shown on the graph.

The measured lengths of successive growth stages converted to the scale of the graph do not correlate with the calculated points using 1.26 as the growth factor. Przibram's growth factor of 1.26 is therefore not the growth factor for any of the species analyzed. As a matter of fact, it has been proved that 1.26 is not the growth factor of other groups of Arthropoda (Calvert, 1929).

The calculated growth factors for the several species of living ostracodes (table 1) indicate that no single factor can be applied to all the growth stages of the same species. Consequently, Fowler's hypothesis that each species has a

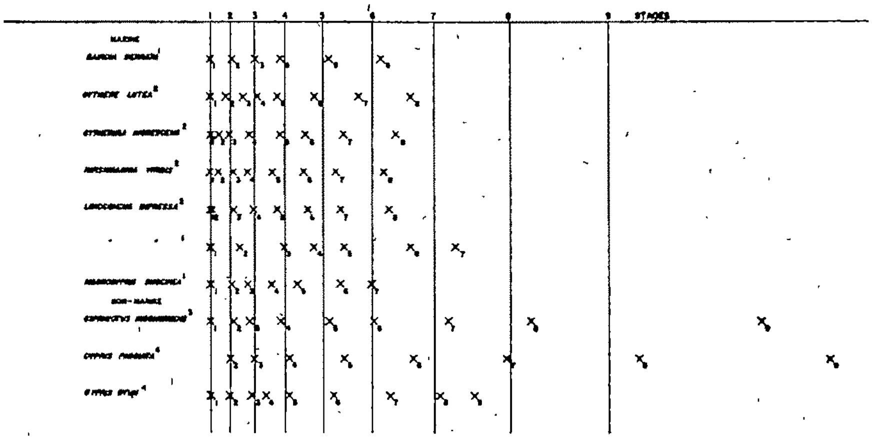

Fig. 1. Graph for nine growth stages calculated on the basis of a growth factor of 1.26, and plotted points (X) of measured lengths of growth stages of living ostracodes converted to the scale of the graph (see text). Subscript numbers indicate the growth stage. There is no record for the first growth stage of *Cypris fasciata,* consequently a scale value of 1.26 was assigned to the second stage. Data from table 1.

definite growth factor is not strictly true in the light of observed data.

Adult ostracodes range in length from 0.5 mm to 30.0 mm. Because the majority of them are less than 2 mm long, the average growth factor for these ostracodes must theoretically be less than 1.5. This is based on the following calculations: The first stage of all ostracodes for which I have been able to obtain data is larger than 0.10 mm. Assuming 0.10 mm as the length of the first stage, the ninth stage was calculated using growth factors of 1.1, 1.3, 1.5, 1.75 and 2.0.

TABLE 2

Calculated lengths for nine stages

Stage	Growth factor 1.1	Growth factor 1.3	Growth factor 1.5	Growth factor 1.75	Growth factor 2.0
1	0.10 mm	0.10 mm	0.10 mm	0.10 mm	0.10 mm
2	0.11	0.13	0.15	0.18	0.20
3	0.12	0.17	0.23	0.31	0.40
4	0.13	0.22	0.34	0.54	0.80
5	0.15	0.29	0.51	0.94	1.60
6	0.16	0.37	0.76	1.64	3.20
7	0.18	0.48	1.14	2.87	6.40
8	0.19	0.63	1.71	5.03	12.80
9	0.21	0.82	2.56	8.80	25.60

This table shows that the size of the adult is directly dependent on the size of the first stage and on the average value of the growth factors between the growth stages; a small average growth factor will result in a small adult, a large average growth factor will result in a large adult.

A study of growth stages in fossil ostracodes is usually initiated through the fortuitous finding of a series of valves of progressive size. These valves all have some features that are considered by the student as diagnostic of a single species, and they usually are from one locality. The valves are arranged in order of increasing size. Variation in shape, ornamentation, hinge structure, and other observable features are recorded. Because the study is based primarily on the fact that the specimens are of progressive size, the following discussion deals with some limitations of the concept of a growth factor.

At each growth stage the size of the individuals can be expected to vary because of hereditary and environmental factors. The frequency distribution of size for individuals of

any given growth stage may for convenience be assumed to take the shape of a normal curve when plotted on a graph. The curves of the frequency distribution of size of individuals in a series of growth stages will appear either as separate curves or as curves with overlapping ends. Some of Fowler's (1909) measurements of Recent ostracodes and my measurements of fossil ostracodes indicate that in some species the curves overlap. Large individuals of one stage may be equal to, or larger than, individuals of the next stage. It should be difficult therefore to differentiate between growth stages of fossil forms because of this overlap in size. Features other than size alone must be relied upon to differentiate between growth stages.

I measured the hinge length, height, and convexity of a growth series of *Aurikirkbya wordensis* (Hamilton) and the greatest length, height, and convexity of *Miltonella shupei* Sohn.[2] Graphs for these measurements indicate that it is impossible to differentiate between growth stages on the basis of size alone. In the above as well as in growth series of other species from the Permian of the Glass Mountains, Texas, it is not possible to distinguish between most of the growth stages on the basis of any other feature of the valves.

Growth stages of individuals of living ostracodes differ from each other in size, in the number of appendages, in size and type of organs, in hinge structure, and in the extent of fusion of the duplicature. In fossil ostracodes, the stages differ in so far as the above factors are reflected in the structure of the valves.

Molts of ostracodes may differ from each other only in size, or may not differ at all. When the molts are between two successive growth stages, they will differ in the same manner as the growth stages.

I do not mean to imply that studies of growth series should be abandoned. On the contrary, growth series of *Aurikirkbya wordensis* (Hamilton) enabled me to restrict that species and to differentiate between it and a closely allied concurrent species. Growth series of *Miltonella shupei* Sohn enabled me to place within this species individuals which, when found

[2] These two genera are described in "Growth series of ostracodes from the Permian of Texas": U. S. Geol. Survey Professional Paper 221c, 1950, pp. 33-39.

isolated, could incorrectly form the basis for several new species. I wish to emphasize the fact that the available biological data are not adequate to solve the problems of the number of instars in ostracodes, of postmaturity molting, and of the number of molts between instars.

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GRAPHIC ANALYSIS OF DRIFT TOPOGRAPHIES*

ROBERT V. RUHE

ABSTRACT. A useful criterion for differentiation of glacial drifts of different ages is a comparison of their topographies. In general, analyses of drift topographies have been qualitative. A quantitative method of analysis which can be presented in simple graphic form is proposed. Time relationships of the drifts are determinable by interpretation of the frequency curves of drift topographies. Relationships of the Wisconsin drifts of northwestern Iowa are demonstrated by application of a graphic method.

INTRODUCTION

T. C. CHAMBERLIN (1878) emphasized the significance of differences in topographic expression as a means of differentiating glacial drifts. Since this pioneer work, topographic form has been utilized as a criterion of differentiation. However, analyses of drift topographies have been mainly qualitative. Lengthy, detailed descriptions have been employed to demonstrate existing differences. As a result, surfaces of considerable extent were interpreted on the basis of generalizations.

Topographic maps have been used to demonstrate differences of drift topographies. Alden and Leighton (1917, pp. 60-77) used portions of U. S. Geological Survey topographic maps to illustrate differences between Iowan and Kansan drift regions of northeastern and eastern Iowa. An adequate picture of a very small part of the drift regions is thus available. The major portions of the regions where topographic surveys had not been made were, of necessity, described in the accompanying general discussion.

Carman (1931, pp. 40-48, 103-105) encountered difficulty in describing the topographies of the drifts in northwestern Iowa that he delineated as Iowan and Kansan. Restudy of these drift regions (here reclassified as Tazewell and Iowan) demonstrated to the present writer that they cannot be contrasted qualitatively. The regions contain the same topographic units. Comparison on a descriptive basis shows only that the drift topographies are similar. However, if a quantitative method of analysis is used, differences are noted.

In recent years aerial photographs have been used exten-

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sively in glacial studies. Interpretations based upon use of these field aids have also been mainly qualitative.

A method that reduces expressions of drift topographies to a concise form has not been presented, to the writer's knowledge, in the literature. The following method has been found useful.

GRAPHIC METHOD OF ANALYSIS

In regions where topographic maps are lacking, analysis of slopes and relief can be made by a study of highway profiles. Profiles of primary roads are available in many states at the offices of highway commissions or offices of district resident engineers. Most glacial drift surfaces are traversed by networks of these primary roads.

The factors (1) slope and (2) relief are determined directly from the highway profile. In the generalized profile (fig. 1) slope in percent (s) is computed:

$$s = \frac{y}{x} \times 100$$

y is the difference in elevations between two adjacent high and low points in an increment of the traverse (X), and x the horizontal distance between those points. For example, slope of the portion of the profile ab is determined:

$$s = \frac{y_5 - y_2}{x_1 - x_0} \times 100$$

Similar computations are made for the portions of the profile bc, cd, etc. Relief is determined:

$$r = y_m - y_n$$

y_m and y_n are the elevations of adjacent high and low points in an increment on the profile. For example, relief on the part of the profile ab is computed:

$$r = y_5 - y_2$$

Similar computations are made for the parts of the profile bc, cd, etc.

Slopes and relief of the highway profile are analyzed statistically by determining the values of these factors along the line of traverse (X). Brackets of quantitative values may be established. Slopes may be grouped conveniently into values which vary from 0-3, 3-6, 6-16, or 16-40 percent; relief ranges may

also be established, such as 20-40, 40-60, 60-80 feet, etc. Units are thus established which can be utilized for statistical purposes.

Analysis of frequencies of slope and relief units is possible if computation of slope and relief is made within equal increments of the total distance of the traverse (X). In figure 1:

$$x_1 - x_0 = x_2 - x_1 = x_3 - x_2 \dots .$$

and

$$(x_1 - x_0) + (x_2 - x_1) + (x_3 - x_2) \dots . = X$$

For example, a traverse (X) consists of 100 increments. Slopes of 0-3 percent exist in 36 of the increments, slopes of 3-6 percent in 42 of the increments, slopes of 6-16 percent in 19 of the increments, and slopes of 16-40 percent in 3 of the increments. Frequencies in percent of the slope ranges are:

Slope	Frequency-percent
0-3	36
3-6	42
6-16	19
16-40	3
	100

Several traverses may be analyzed and the average frequencies of each slope range determined. Results of the computation may be represented graphically in bargraphs or frequency curves. Values obtained by interpretation of a net of primary roads in a region covered with glacial drift can thus be compared with values obtained from a study of profiles of another region. Comparison of drift topographies is reduced to a comparison of mathematical curves.

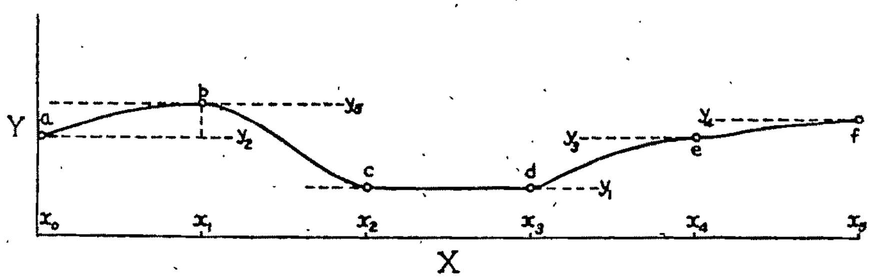

FIG. 1. GENERALIZED HIGHWAY PROFILE

Accuracy of the graphical representation of drift topographies increases with the number of profiles analyzed. In northwestern Iowa, five east-west primary roads traverse the Tazewell and Iowan drift regions. Two north-south roads are located in each of the Tazewell and Iowan regions. Distances of fifteen to twenty miles separate the highways. The writer believes that this number of profiles should represent with a reasonable degree of accuracy the topographies of these drift regions.

Use of highway profiles for analytical purposes requires (1) a field check of the geographic location of the traverse to determine whether the true topography of the region is expressed by the profile, and (2) corrections for cuts and fills made in the course of highway construction. Evaluation of these factors is necessary for an accurate analysis. For example, in many places in the Kansas drift region of southwestern Iowa highways are emplaced along narrow topographic divides where gentle slopes exist. Profiles normal to the divides show the steeper slopes that are characteristic of the region. In this case the profile of the primary road does not express the true topography. Cuts and fills reduce the slopes of a drift surface. The highway profile must be converted to the true topographic profile by the addition of the depths of cuts and heights of fills to the convex sides of the swells and sags respectively of the highway profile. Field study is necessary to check the corrected profile. Corrected profiles should be used in the statistical analysis of drift topographies.

An alternative approach to a quantitative study of a drift surface may be made by using aerial photographs upon which altitudes taken during altimeter traverses have been plotted. Profiles are readily constructed and the above method of analysis employed.

A shortcoming of this quantitative method is that glacial constructional forms (end moraines, drumlins, etc.) must be incorporated in the profile analysis. Erosional and constructional slopes may fall within the same range and be grouped together. It is possible that an end moraine unmodified by postglacial erosion may be represented by a frequency curve which is the same as or very similar to the curve of a dissected ground moraine of an older drift. Therefore the graphic method is applicable only to comparisons of con-

structional topographies or erosional topographies if entire drift regions are analyzed. Modified and unmodified drift surfaces may be contrasted if the analyses are restricted to the same types of topography, for example, ground moraines.

An evaluation of the bedrock or other preglacial surfaces is necessary in order to determine their influence upon the present drift surfaces. For example, the frequency curve of the topography of a thin older drift mantling a relatively flat bedrock surface may be quite similar to the curve of a young unmodified till plain where bedrock does not influence the surface expression of the drift. Field study, however, would show these relationships. In the following section a graphic method of analysis is applied to the drifts of northwestern Iowa. The thicknesses of these drifts are believed to be of such a magnitude that the existing surfaces of the drifts are not influenced by the character of their preglacial surfaces.

APPLICATION OF METHOD

Four Wisconsin drifts have been identified and mapped recently by the writer in northwestern Iowa; the drifts are recognized as the Iowan, Tazewell, Cary, and Mankato. Field study showed that the Iowan and Tazewell drifts are well drained and have had integrated drainage systems developed on their surfaces. Undrained depressions are lacking. These two drifts are very similar topographically. Local areas of level, undulating, rolling, and dissected ground moraine occur, and because of this relationship the regions cannot be differentiated on a qualitative basis. However, the frequency of occurrence of these topographic units differs (fig. 2). The regions may be differentiated on a quantitative basis.

The Iowan and Tazewell drifts are bordered to the south in western-central Iowa by the Kansan drift. This older drift differs distinctly from the younger drifts and is maturely dissected and characterized by steep slopes. The difference is particularly evident when the frequency curves are compared.

The Cary and Mankato drifts are very similar topographically but differ decidedly from the Iowan and Tazewell drifts in this regard. The two later drifts are margined by vigorous end moraines with well-aligned trends. End moraines also exist at variable distances behind the marginal moraines. Intermorainic till plains of low relief constitute appreciable

portions of the drift regions. Field study showed that both regions are very poorly drained in the end- and ground-morainal areas. Integrated drainage systems have not been established on these drift surfaces. Undrained depressions are abundant. Similarity of the ground-morainal topographies of the Cary and Mankato drift regions is demonstrated by the Cary and Mankato curves (fig. 2). Evidence that the

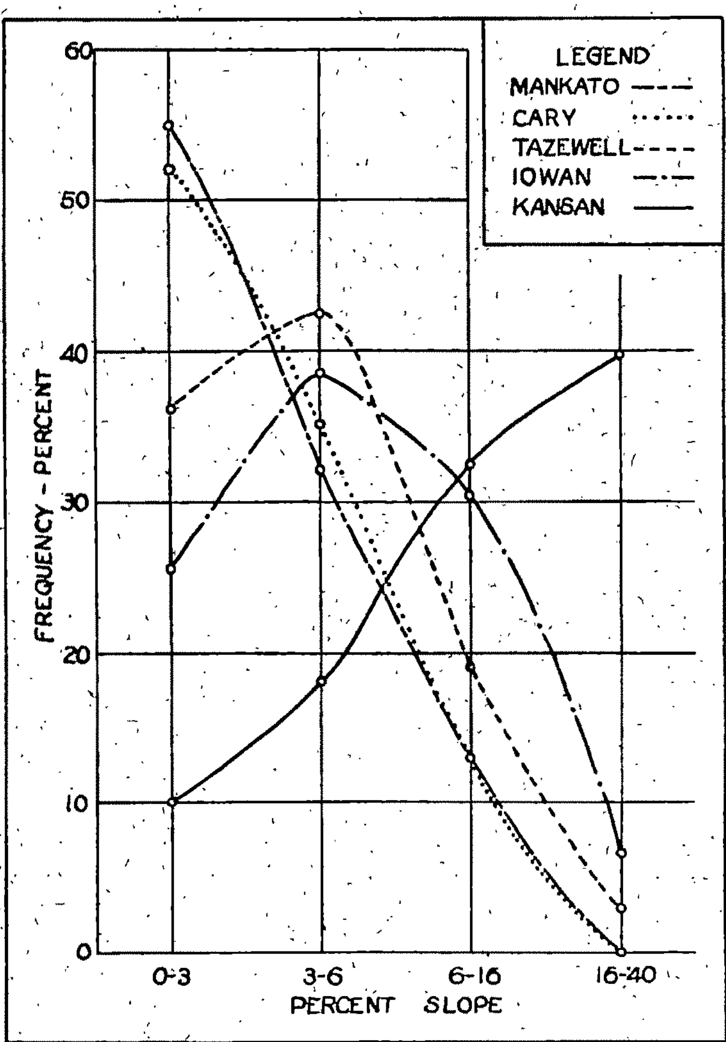

FIG. 2. FREQUENCY CURVES OF GROUND-MORAINAL TOPOGRAPHIES

Iowan and Tazewell topographies differ from the Cary and Mankato is shown by the slope curves of the four drifts.

The frequency curves in figure 2 represent the topographies of the ground moraines of the various drifts. No end moraines exist in the Kansan or Iowan regions. A subdued, patchy end moraine that exists at or near the margin of the Tazewell drift is excluded from the analysis. The end moraine constitutes only one to two percent of the Tazewell drift region. The frequency curves of the Kansan, Iowan, and Tazewell therefore essentially represent the topographies of these drift regions. In figure 3 the topographies of the whole of the Cary and Mankato regions are represented. End and ground moraines are included in the analyses. Similarity of these drift topographies is evident.

Computation of the frequency curves of the slope topographies of the Kansan and Wisconsin drifts is based upon a slope study by the soil survey personnel of the Iowa Agricultural Experiment Station (1949).

RELATIONSHIP OF TOPOGRAPHIC EXPRESSION AND TIME

Frequency curves of the Kansan, Iowan, Tazewell, Cary, and Mankato topographies show the time relationships of these drifts. Peaks of the frequency curves shift from low-slope to high-slope values as the age of the drift increases. Peaks of the Mankato and Cary curves fall within the 0-3 percent range whereas those of the Tazewell and Iowan curves shift to steeper slope values, 3-6 percent. The Kansan modal is in the steepest slope range, 16-40 percent.

Pertinent to study of the Wisconsin drifts is the relationship which exists between the Mankato, Cary, Tazewell, and Iowan curves (fig. 2). Similarity of the Mankato and Cary curves (also fig. 3) indicates that these two drifts are closely related in time. The same relationship exists between the Tazewell and Iowan curves. Comparison of the curves of the Mankato and Cary to the Tazewell and Iowan indicates that the major time break in the Wisconsin sequence occurred during the Cary-Tazewell interval. Field study showed that integrated drainage systems have been established on the two older Wisconsin drifts but not on the two younger drifts. An interval of time of substantial duration was necessary for the establishment of drainage. Comparable time intervals between the Mankato and Cary

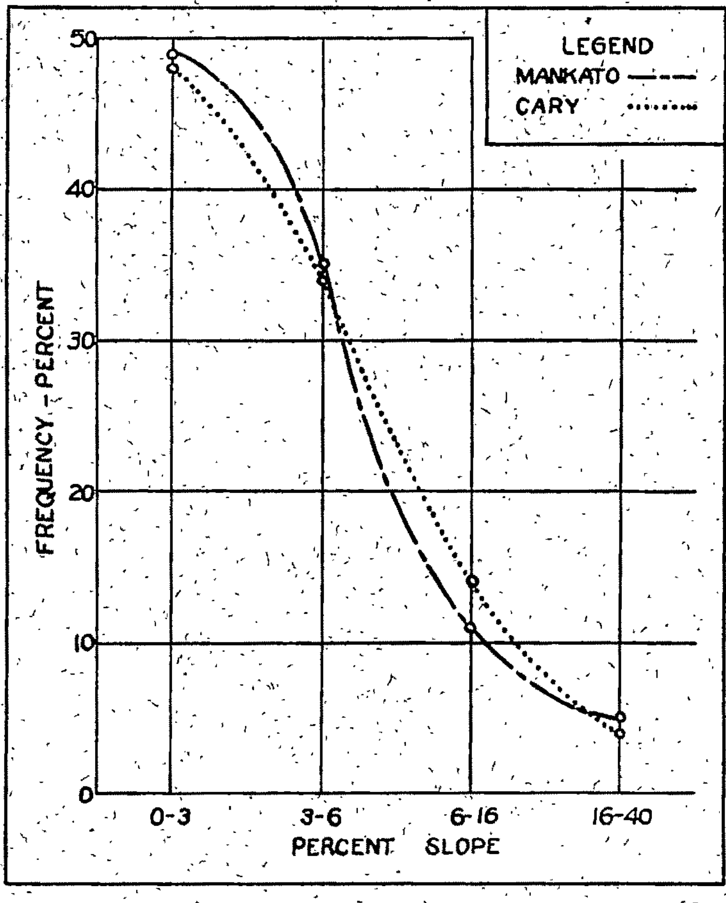

FIG. 3. FREQUENCY CURVES OF DRIFT TOPOGRAPHIES

and the Tazewell and Iowan are precluded by the similarity of existing topographies as demonstrated by the frequency curves.

CONCLUSIONS

Quantitative analyses of drift topographies can be made by the simple method detailed in the foregoing statement. Analyses can be presented in simple graphic form. Comparison of drift topographies is reduced to a comparison of mathematical curves. Knowledge of the time relationships of the drifts is gained by interpretation of these curves.

ACKNOWLEDGMENTS

Appreciation is expressed to Dr. R. F. Flint, Department of Geology, Yale University, Dr. H. G. Hershey, Iowa Geological Survey, Dr. A. C. Trowbridge, Department of Geology, State University of Iowa, and Mr. K. E. Anderson, Iowa Geological Survey, who have read and criticized the manuscript. The writer appreciates the criticisms of Drs. Guy D. Smith and R. W. Simonson, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture, and Dr. F. F. Riecken and Professor A. J. Englehorn, Department of Agronomy, Iowa State College.

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REVIEWS

An Advanced Treatise on Physical Chemistry. Volume I. Fundamental Principles; The Properties of Gases; by J. R. PARTINGTON. Pp. xlii, 948. London, 1949 (Longmans, Green and Co. Ltd., $16.00). The publication, particularly in English, of the first volume of a new three- to four-volume advanced treatise on physical chemistry will be welcome to many.

Partington's contribution differs from other encyclopedic works of its type in being the work of a single author, rather than the collaborative effort of a group of experts. This lends to the book a pleasant sense of unity: all the topics are treated from approximately the same level, and there is less tendency to stress a particular approach to a topic at the expense of viewpoints other than the author's. It also means that there is very little original material or interpretation in the book, although critical evaluations of conflicting theories and observations are often referred to when they are to be found in the literature.

In the preface, which is well worth reading for its caustic comments on the state of scientific literature in England and America, Partington claims to be particularly interested in the experimental side of the science. This bias, however, does not prevent him from giving excellent summaries of such theories as may be of value to the experimentalist. This means, in fact, most of the important theoretical topics of physical chemistry.

This first volume of the set begins with a concise mathematical introduction followed by a presentation of thermodynamics, emphasizing the practical applications of the methods, rather than the formalized axiomatic derivation of the science. Next comes a brief treatment of important results of the kinetic theory of gases, based primarily upon the free-path concept, instead of the fundamental integro-differential equation. The section on statistical mechanics, which follows, stresses the Maxwell-Boltzmann formulation of the theory, as being of most importance for physico-chemical applications, and includes a full discussion of methods of computing thermodynamic functions from molecular models. The more sophisticated approaches to the theory are mentioned, but not emphasized. A rather brief section on wave mechanics, concerned primarily with solving the Schroedinger equation for the hydrogen-like atom concludes the exposition of fundamental principles.

The practical part of the volume begins with a section on temperature, which includes information on thermoregulators, thermometers, fixed points, and a variety of other useful data. This is followed by

descriptions of special techniques for experimentation at high and low temperatures.

The final and longest section of the volume is devoted to properties of gases. The principal sub-headings include: pressure-volume-temperature relations of gases, experimental; critical phenomena; equations of state; densities and molal weights of gases and vapors; specific heats of gases; viscosities of gases; conduction of heat in gases; diffusion of gases; and gases at low pressures. For all these subjects, attention is given to methods of obtaining the data, as well as to the ways of correlating and interpreting the results once they have been secured. Numerous empirical equations are given, with values of the constants for substances to which they are applicable, and there are also extensive tables of numerical data. In addition, pertinent theoretical discussions are included at appropriate points.

Professor Partington has accomplished a remarkable job of surveying the literature from a very early date up to a time only shortly before the appearance of this volume. In several instances, work appearing in 1949 is referred to, although Partington disclaims any responsibility for the validity of such material. In addition to the very complete footnote references—18,145 separate citations are said to be included—each major section contains a bibliography of pertinent textbooks and monographs, and there are also special bibliographies on certain special topics such as the one on statistical calculations of entropy. One of the most frequent uses of the work will probably be as a guide to the literature in a particular field.

There are, unfortunately, a few defects which require comment. In a work of this magnitude executed by a single author, occasional errors of fact or of interpretation are almost inevitable. The user of the book will therefore be well-advised to verify the statements from the original literature before relying too strongly upon data contained in any book of this type. An example of such an error is the implication, on p. 825, that the law proposed by Lennard-Jones for the *intermolecular* potential energy can be applied to the intramolecular binding of atoms.

Although the subject index is rather more complete than in many English works, it is not up to American standards, and, unfortunately, the table of contents covers only major sections, and does not contain the detailed outline of the organization of the work which is so helpful in becoming acquainted with a reference book of this sort. This is particularly unfortunate since the organization of the book itself is not too consistent, and in several cases material

which the reader might expect to find in one section is taken up somewhere else. Thus, the London theory of van der Waal's forces is taken up in the chapter on the equation of state, and the quantum theory of magnetism under low temperatures, whereas both of these topics might be expected to be found in the discussion of wave mechanics. This weakness could easily be remedied, and the value of the book greatly enhanced by including in the final volume a detailed analytical table of contents and a really good index to the whole work.

The book as a whole is to be highly recommended as a very valuable guide to the literature of physical chemistry. It will be particularly valuable to those who are not specialists in the subject, but need to use either the concepts or the data of one of the fields of physical chemistry in their own work. This use by non-specialists will be facilitated by the author's thorough and unsophisticated treatment. The work should be a necessary part of reference libraries in all fields of science where physico-chemical data or methods are occasionally required. The appearance of the second volume—said to be now in press—and its successors will be eagerly awaited. HENRY C. THACHER, JR.

An Introduction to Crystallography; by F. COLES PHILLIPS. Pp. ix, 302; 500 figs. London, 1947 (Longmans, Green and Co., \$6.50).—This book is intended as an introduction to the study of crystallography, not only for mineralogists and crystallographers, but also for other scientists—chemists and physicists—whose work with crystalline substances may require a basic knowledge of the elements of crystallography.

Mr. Phillips wisely chooses to begin with a study of the elements of external rather than internal symmetry; for, as he states in his Preface, "the student . . . cannot see and handle the atomic structure, and check for himself the regular arrangement, in the same direct way in which he can handle the crystals themselves and check the regularity of angular relationships of the faces by direct goniometrical measurements until the existence of an orderly structure in the crystalline state becomes something much more real to him than a plausible explanation of certain diffraction effects." The introductory chapters trace the development of "classical" crystallography—pre-x-ray crystallography, it might be called—and discuss the seven crystal systems. A short chapter on optical goniometry is followed by a comprehensive account of the thirty-two crystal classes, using the Hermann-Mauguin system of notation. An excellent innovation has been to include, as examples in

each class, not only naturally-occurring minerals but synthetic chemical compounds as well—a feature which should put the chemist somewhat at ease "in his own environment." Chapters on composite crystals, mathematical relationships (assuming only a knowledge of spherical trigonometry), and crystal drawings complete Part I.

Part II of the book is devoted to the internal structure of crystals. A chapter on the elements of internal symmetry is followed by a thorough development of the study of the 230 space groups. The final chapter relates the external form of the crystal, its habit, to the internal structure. A short appendix explains the Schoenflies system of notation for the benefit of those who may encounter it in earlier papers. A final favor to the chemist is an index of chemical ormulae.

Illustrations are excellent and the format allows easy and enjoyable reading. The book may be used advantageously by anyone preparing for a serious study of crystallography.

WALDEN P. PRATT

Stereograms for the Determination of Plagioclase Feldspars in Random Sections; by W. NIEUWENKAMP. Pp. 29, quarto, plates I-XIII. Utrecht, 1948 (Spectrum Publishers; Edward Stanford Ltd., London W.C. 2, agents, $4.64). In conventional petrographic technique, a thin section of a rock must be searched for grains of plagioclase that have special orientations suitable for the determination of the composition by means of extinction angles. The method depends upon the assumption that many grains have the same composition, an assumption that is not always valid. There are only two alternatives: (1) with a universal stage any grain may be turned into a significant orientation and the required extinction angle then measured; (2) if the crystallographic orientation of a grain can be determined, an extinction angle will then give the required composition. Both methods are used in determinations with the universal stage; the second method, however, is now made possible without such expensive special apparatus, by the use of the new procedures described by Nieuwenkamp.

The orientation of an arbitrarily selected grain involves three independent co-ordinates; the composition is effectively a fourth. If the grain is twinned, three independent observations are obvious, namely the positions of extinction in the two twin parts and the "strike" of the composition plane. Nieuwenkamp's important contribution is his development, or discovery, of an easily-measured fourth independent observation that makes possible a systematic

procedure for determining the four unknown co-ordinates of orie tion and composition. The new variable is the *ratio of the fringences* of the two parts of the twin, a quantity that ca measured without knowing the thickness of the section.

The ten "stereograms" are cylindrical equidistant projectior plagioclases of various compositions (0, 10, . . . , 70, 80 an anorthite), showing extinction angles in black contours anc rithms of birefringences in red, for all possible orientations c thin section. Unfortunately, the method of use of these cl described rather poorly, although in fact the method is ra simple. A "pointer" is used, consisting of a movable line seg held parallel to one of the axes of the chart. The length and orie tion of the pointer are determined by the twin law, which is normal assumed to be the albite law until proved otherwise. At the ends of the pointer four constants (extinction angle and logarithm of the birefringence for each part of the twin) are read by interpolatio between the contour lines of the chart. The pointer is systematical moved about on one chart after another until the two observe extinction angles are found, and the difference of the logarithms of the corresponding birefringences (i.e., the log of the *ratio of the birefringences*) is compared with the observed value to determin whether the correct chart has been found. Interpolation is possible between successive charts, just as it is possible between successive contour lines, and the result is a determination of the anorthite content with accuracy comparable to that of the original data on which all extinction angle charts are based. The error is not likely to be more than about 4%.

The choice of length and orientation of the pointer to correspond with the twinning law assumed is discussed all too briefly at the end of the book, under the heading "Plagioclase twin operations in cylindrical [equidistant] projection." Indeed, the discussion of principles throughout the book is almost unworthy of the quality of the charts and of the importance of the method. The reviewer is particularly pleased with the overall simplicity and elegance of the method under review. He sincerely regrets that more space was devoted in the text to a thorough discussion of principles, po working the examples into the text instead of placing them toge at the beginning. The very fact that the method succeeds at all solving so complex a problem (four equations in four unknowns remarkable; that it does so quickly and easily is all the mo important. Its potentialities should be explored to the fullest by petrographers.

HORACE WINCHELL